

Qualitative Validation of Lifting Body VTOL with Stagnation Plates

Highlights:

- A new approach for Lifting body vertical takeoff is presented with increased efficiency over existing aircraft.
- Energy intensities of airplanes are more than 100 times the benchmark of skin friction on the fuselage, with >90% reductions attainable.
- Jet-, prop-, and down- wash are normally prominent causes of lost work when including the additional engine lost work generated to produce the wash momentums.
- Use of flaps to gain altitude are extremely energy inefficient; generating lost work from downwash, jetwash, and turbulence.
- Advanced pressure contour engineering can convert fuselages to lifting bodies and thrusting bodies to mitigate lost work.
- Use of ducts through fuselages can further reduce the lost work due to appendages such as engines, nacelle, large wings, and stabilizers.
- Battery power mitigates combustion losses and emerges as high performance, achieving jet engine speeds, with advanced pressure contour engineering.
- Free flight exhibits anterior recovery and aft recovery steps that approach reversible mechanisms to recover the energy of lift pressures prior to dissipation into lost work, enabling much higher flight efficiencies than possible with downwash mechanisms.

Abstract

The term lifting body aircraft has become synonymous with flying wing aircraft, however the term broadly applies to vehicles where lift pressures are generated directly on the fuselage. A new design generates these lift pressures using a vertical duct through the fuselage aligned with a horizontal-flow blower below the duct to generate lift pressures on the vehicle's lower surface. This lifting-body design emerges as useful in view of lost work analyses with findings that lost work from a fixed-wing airplanes' jet-, prop-, and down- wash are typically prominent, and the lack of activity to mitigate the "wash" losses suggests the magnitudes of these losses have been underestimated. The use of wing flaps to increase altitude approximately doubles the respective lost work versus vertical takeoff methods since the resulting lost work appears as both jetwash and downwash. Advanced pressure contour engineering can mitigate the wash losses and aerodynamic resistances, which when combined with battery power, can reduce energy intensity of aircraft by >90%. Approaches to mitigating the lost work teach toward aircraft with lifting and thrusting body designs with minimal wingspans. Proof-of-concept computational fluid dynamic studies substantiate the pressure contour engineering approaches. This paper details: a) the base-case lifting body design, b) the computational fluid dynamics verification, c) the fundamental principles which create lift and improved efficiency, and d) a lost work analysis for airplane transit with closure of the energy balance. A comprehensive explanation of how cruising airfoils recover the energy of lift pressures, versus loss as downwash, clarifies how air pressures influence airflow over airfoils.

Keywords

VTOL aircraft, VTOL (Vertical Takeoff and Landing), Lift, Ground effect aerodynamics, Lost work, drag, efficiency

Introduction

Helicopters are the mainstay of Vertical Takeoff and Landing (VTOL) aircraft in modern society, but they are complex, inefficient, and relatively expensive [1, 2]. An effective means to generate VTOL lift pressures on a fuselage could eliminate the rotary wing's costs and complexities while streamlining cruising speed configurations.

Base case designs on ground-effect flight railcars identify that a 90% reduction in energy intensity is possible for rail transit due to significant reductions in mechanical/rolling resistance and higher speeds on existing infrastructure. These transit advances combined with autonomy, AI, and improved scheduling can lead to substantial reductions in ground transit times, costs, and environmental impact. These advances can be disruptive to the ability of air transit to compete in large market sectors and provide the incentive for higher-risk higher gain advances in air transit.

Computational fluid dynamics (CFD) quantifies how air flow generates pressures on fuselage surfaces. A critical aspect of innovation and advancement in lifting body vertical takeoff designs is the ability to understand how air flow leads to changes in surface pressures and reduces lost work during the aerodynamic transformations.

The paper entitled "An Airfoil Science Including Causality" identifies three principles which define how air flow generates aerodynamic lift [3]. Extending upon the three principles, a hypothesis emerges that advances are possible with air transit using battery power and by reducing jetwash and downwash lost works. This paper progresses: a) from lost work analyses on a 200-passenger jet airliner, b) to proof-of-concept computational fluid dynamic analysis (CFD) of novel lifting-body designs, and c) to a critical analysis of the results toward a proof of concept.

Background

New Aero-Engineering Approach

A new approach to vehicle design places an emphasis on vehicle structures and propulsor locations to lead to substantially-reduced drag while simultaneously generating aerodynamic lift [4]. The approach focuses on using recent advances in understanding how airflow behaves on boundary layer surfaces [5-8]. These technologies are then applied alongside techniques to use propulsors to adjust airflow over the trailing surface of an airfoil and minimize overall turbulence generated by an airfoil [9-11]. The technology is based on the engineering of pressure contours of vehicle surfaces toward higher performance. For example, an upper-surface trailing-edge ducted fan on the upper portion of a trailing taper can mitigate boundary layer separation over the trailing taper while generating aerodynamic lift.

Initial studies resulting from these approaches taught toward ground effect flight to realize very high lift-to-drag ratios (L/D) and provides a path for evolution to multimodal transit and substantial reductions in transit energies, times, and costs using existing infrastructure [12]. Ground effect includes significant increases in lift and vehicle efficiency associated with flight near low surfaces [13-15]. Performance limitations of initial vehicle designs reside in using alternative suspension at lower speeds and reduced lift at increasing distances from the ground.

The current paper pursues an extension of the initial applications of pressure contour engineering to include the use of vertical ducts through the fuselage to generate lift on the vehicle's lower surface. The

path of evolution extends beyond ground effect flight, to the broader topic of improved vertical takeoff and landing approaches through pressure contour engineering.

First Approximation to Vertical Takeoff Efficiency

During vertical takeoff and hovering, heavier-than-air vehicles generate lift pressures with rotary wings or blades [16, 17]. The upward force is balanced with downward momentum of air per Equation 1:

$$Force = \dot{m}_e U_e - \dot{m}_0 U_0 \quad \text{with SI units of } \left(\frac{kg \, m}{s^2} \right) \text{ or } (N) \quad (1)$$

where F is force, $\dot{m}$ is mass flow rate, U_e is the exiting velocity, and U_0 is freestream velocity; all four taken in the vertical vector for lift calculations. In the limit of zero upward velocity, the vertical free stream velocity is functionally zero which simplifies Equation 1 through removing the second term.

A mechanical energy balance on the air stream for stationary hovering written in terms of power yields Equation 2. Equation 2 provides power in relation to mass flow rate in the limit of zero altitude change:

$$Power = 0.5 \dot{m}_e U_e^2 \quad \text{with SI units of } \left(\frac{kg \, m^2}{s^3} \right) \text{ or } (W) \quad (2)$$

The performance of two different hovering vertical lift propulsors of: a) areas A_1 and A_2 and b) equal forces of $\dot{m}_{e,1} U_{e,1} = \dot{m}_{e,2} U_{e,2}$, within which substituting $\dot{m} = \rho A U$, provides a relationship between the velocities and areas presented as Equation 3.

$$\frac{W_2}{W_1} = \frac{Power_2}{Power_1} = \frac{U_{e,2}}{U_{e,1}} = \sqrt{\frac{A_1}{A_2}} \quad \text{for same upward force} \quad (3)$$

Equation 3 provides a simplified interpretation that the velocities and areas to provide a constant lift are thermodynamic properties of state under the assumption of reversible transformations within the lift areas and propulsor. Since potential energy is stored in the system (i.e. "vehicle"), the energy stored in the energy of the downward air flow leaving the vehicle is lost work (LW).

As a property of state, Equation 3 is independent of the method in which downward velocity is created; it applies equally well to a ducted fan and as to a coupled system including a ducted fan surfaces designed to create an expanded lift area. The equation does assume the same momentum-generating surfaces on upper and lower surfaces of the ducted fan or vehicle for the comparison of vehicles.

The objective is to compare lost work for four flight methods as ideal cases. For each flight method process, a form of lost work (LW) is $LW = 0.5 \rho A U^3$, which is the work of the kinetic energy of the air flow which is lost to the surroundings. The following paragraphs identify the areas and velocities for each duct and lifting body process.

For ducted fan vertical takeoff lift:

$$Force = \dot{m}_e U_{Y,e} = \rho A_{DF} U_Y^2 \quad (4)$$

Where the subscript **DF** indicates ducted fan. For discussion purposes, velocity and pressure to have force equivalents of $P_{DP} = \rho A U^2$. Additional subscripts of **LB** and **GE** indicate lifting body and ground effect.

For lifting body vertical takeoff lift:

$$Force = P_{LB} A_{LB} = 0.5 \rho A_{LB} U_Y^2 \quad (5)$$

Pressure is replaced with the dynamic pressure's equivalent velocity. The area is considered the planform area of the lifting body. When the "**P A**" term accounts for both upper and lower surfaces, the "**0.5**" of Equation 5 doubles to "**1.0**" if the lift forces acting on the upper surface are assumed to have the same magnitude as the forces on the lower surface. The lower surface lift pressures provide a direct relation between pressure and downwash velocity.

For ground effect lift the ground blocks downward velocity, but the force equation remains:

$$Force = P_{LB} A_{LB} \text{ for ideal ground effect} \quad (6)$$

In ground effect, a vehicle with a lower surface cavity creates a low clearance. Pressure expansion occurs under the perimeter, rather than directly downward, with lost work provided by Equation 7.

$$\frac{\Delta LW_{LB}}{\Delta t} = 0.5 \rho A_{Gap} U_{XZ}^3 \quad (7)$$

Where A_{gap} is the area of the clearance below the planform perimeter and defines the equivalent term A_{GE} used in subsequent discussions. In efficient ground effect flight, the vehicle realizes the lift provided by A_{LB} while losses are proportional to the much lower A_{GE} . The dynamic pressure velocity term is represented by V rather than U to indicate that the flow is in the lateral directions rather than vertical flow.

Subsequent discussions will include lift from steady-level flight. For a lifting body in free flight, lift is expressed as a lift coefficient per Equation 8, where V is the horizontal velocity of the vehicle relative to freestream flow.

$$Force = Lift = 0.5 C_L \rho A_{LB} V_{LB}^2 \quad (8)$$

where LB includes lifting bodies, airfoils and wing sections. V is translational velocity in the x direction of the vehicle.

The Bell Nozzle

Whereas in the bell nozzle of a rocket engine air is rapidly expanding due to the release of heat from combustion, very little expansion of air occurs naturally in the nozzle of a jet engine. As a result, a bell-shaped discharge of a vertical fan experiences minimal increases in pressure with the prominent feature of high-velocity air streaming through the center of the nozzle. A hypothesis for generating higher pressures on the inner surfaces of a bell nozzle comprises:

Hypothesis – *a centrifugal impeller rotating about a vertical axis in the center of a bell nozzle can be operated with lower pressure forming on the upper-surface eye of the propeller with radial acceleration of air which would impact the inner surface of the bell nozzle and generate lift pressures.*

A goal is to replace the fan of a ducted fan with an impeller and bell nozzle below the duct to create an A_{LB} which is greater than the A_{DF} per Equations 4 and 5. At a constant lift force, a larger area results in reduced work and increased efficiency to generate the same lift. While the introduction to this analysis is in terms of an impeller and bell nozzle, any efficient approach to generate horizontal flow will perform sufficiently well. The shape of the perimeter is not limited to that of the circular shape of a bell nozzle.

A New Transit Paradigm

A recent paper estimates the causes of lost work for a train from basic skin friction to the total energy intensity in Btu per passenger mile as summarized by Table 1. The analysis reveals an 83-fold increase in energy intensity from the fuselage to the total and corroborates analysis of digital prototypes for ground-effect flight railcars which consume less than 10% of the Btu per passenger-mile consumed by current passenger trains. Substantial reductions in railcar transit energy and times presents a new paradigm where questions emerge on the ability of airplane transit to compete in substantial market segments.

The initial value of the energy intensity of skin friction for an aircraft fuselage of 7 Btu/(pax-mile) of Table 1 can be expressed as an equation with a factor (k_f) of Equation 9.

$$D_{f,v} = k_{occupancy} k_f 0.5 C_D \rho A_{Wetted} V^2 \quad (9)$$

Where k are factor multipliers, the subscript "occupancy" is reciprocal fraction seat occupancy, and subscript f specifies ratio of per seat area of airplane versus per seat wetted area of a railcar.

The extended analysis of Table 1 identifies an aircraft fuselage having a resistance lower than a railcar "fuselage" and the higher energy intensities of current airliner transit. The subsequent background discussion provides a framework for completing the lost work analysis of an airliner, with the results section focusing on proof-of-concept approaches to reduce the lost for airplane transit by more than 90%. A purpose of this paper is to complete estimates of lost work by category for the Jet Airliner of Table 1.

Table 1. Lost work in terms of energy intensities (E) based on 18.7 Btu/(seat-mile) fuselage (*viscous drag) and resulting in Btu/(passenger-mile).

Train (90 mph)		Jet Airliner		GOAL (140 mph)	
Fuselage*	19	Fuselage* ($D_{v,f}$)	7	Fuselage* ($R_{1, viscous}$)	12
Pressure Drag	18	Hotel (L_H)		Hotel	12
		Appendages ($D_{v,A}$)		Spanwise Dissipation (R_P)	10
Rolling/Mechanical	46	Pressure Drag (D_p)		Jetwash, Rolling, Cont.	10
Hotel	146	Velocity Penalty (P_{vel})		Velocity Penalty	40
Braking & Waste	64	Takeoff/Alt (long haul)		Braking etc.	10
Engine	500	Jetwash			
50% Occupancy	790				
Total		Total (long haul)	2150		
		Total (short-haul)	3470		
				94	

Fuselage Benchmark

The Fuselage benchmark of 19 Btu/(passenger-mile) is based on actual performance as well as fundamental calculations relating to skin friction [ref Davis, Feasibility). The value of 7 Btu/(passenger-mile) for an airliner is based on seating densities of 0.6 seats per m² for a train and 1.6 seats per m² for economy airliner seating, both areas on planform basis.

Actual values skin friction could be lower for the aircraft when accounting for smoother more-streamlined surfaces of the airliner fuselage versus the railcar. The series of equations of Table 2 provide estimates for the lost work items of Table 1.

Table 2. Equation estimates for values of lost work of an airliner where: P is pressure, v is viscous, V is airplane velocity relative to free stream air, F is a multiplying factor, D is drag, f is fuselage, A is appendage, N is a multiplying factor, L is load, H is “on-board-hotel”, LW is lost work, E is engine, Eff is efficiency, JW is jetwash, DW is jetwash, T&A is takeoff-&-altitude.

Velocity Penalty	$D_{Vel} = k_{Vel}(D_{v,f} + D_{v,A} + D_P)$	(A)
	$k_{Vel} = \left(\frac{V_{Cruising}}{90}\right)^2 P_{Cruising} \cong 8.3 \text{ (7.3 = 8.3 - 1) (cruising)}$ 0.235 atm P, 535 mph	(B)
Appendage Drag; Assume	$D_{v,A} = D_{v,f}$	(C)
Pressure Drag	$D_P = k_D(D_{v,f} + D_{v,A})$	(D)
On-Board Hotel	Estimate L_H (e.g., same as $D_{v,f}$)	(E)
Engine	$LW_E \approx \frac{(1-Eff_{Engine})}{Eff_{Engine}} [(LW_{v,f} + LW_{v,A} + LW_P + LW_{Vel}) + L_H]$	(F)
Jetwash	$LW_{JW}^* = \frac{0.5 k_{JW}}{Eff_{Engine}} [(LW_{v,f} + LW_{v,A} + LW_P + LW_{Vel})]$	(G)
Jetwash	$LW_{JW}^* = \frac{0.5 k_{JW}}{Eff_{Engine}} \left[\frac{Eff_{Engine}}{1-Eff_{Engine}} LW_E - L_H \right]$	(H)
Jetwash	$k_{JW} = \left(0.5 C_{D,Wetted} \frac{A_{Wetted}}{A_J} \right)^{0.5}$	(I)
Downwash	$Lost Work DW = k_{DW} \frac{t_{Alt}}{t_{total}} Lost Work JW$	(J)

Values for benchmark fuselage viscous drags can be verified with calculations such as Equation 10 using viscous drag coefficients. An example calculation is provided by Table 3. The basic calculation agrees with the benchmark value of 6.5 (Btu/(seat-mile)) for the energy intensity of a basic fuselage with a deviation of 3.0 depending on specifics of economy class seating and aircraft size.

$$Drag = 0.5 C_D \rho A_{Wetted} V^2 \quad (10)$$

Table 3. Values use to check basic skin resistance of a fuselage.

Fuselage Diamter (e.g. 7373)	3.76 m
Chordwise Spacing of Seats	0.76 m
Wetted Area / Seat (6 across)	1.5 m ² (0.76 X 3.76 π / 6)
Air Density	1.293 kg/m ³
Velocity (V) basis	90 mph or 40.2 m/s
Resistance at Velocity Basis for air density of $\rho = 1.29 \text{ kg/m}^3$	3.127 N/seat or J/(seat-meter) (0.5 * 0.002 * 1.5 * (40.2) ² * 1.29 kg/m ³),
Conversion	4.79 Btu/(seat-mile) at 0.002 drag coef. 6.0 Btu/(seat-mile) at 0.0025 drag coef.

Aerodynamic Drag Losses

Cruising velocities of 450 to 540 mph for airliners are five to six times the 90 mph benchmark of a railcar, resulting in 25- to 36- fold the skin friction relative to the benchmark speeds. Cruising at higher altitude pressures of 0.2 to 0.3 atm pressure reduces the fuselage drag while the lower temperatures can increase resistance up to 20%. The combined impact of higher velocity and speeds leads to a 6- to 12- fold increase in fuselage drag as a multiple of the skin friction. An average combined impact of velocity and pressure is a 9-fold increase in viscous drag. This factor of 9 is identified by Equation 3 of Table 2 along with other approximations of lost work to prepare a closed balance on lost work for an airliner.

Based on the benchmark of a fuselage, the appendages of an aircraft include: a) wings, b) engines/nacelle/props, and c) vertical/horizontal stabilizers. On the low end, a wing planform area is about 1.5 times the fuselage planform area. Taking into account the surfaces stabilizers and engines and height, the wetted surface area of appendages are about equal to the fuselage wetted surface area (Equation 4).

Pressure drag is highly dependent on the surfaces and pitch of the aircraft. During takeoff, pressure drag is higher due to increased pitch of the aircraft. The pressure drag coefficient is not the same for the fuselage and appendages; however, assuming the Equation 5 form as provided in Table 2 provides with a factor “S”. The ratio of pressure drag to viscous drag for a cruising airliner is reported to be about one-to-one. Pressure drag is higher for takeoff.

Engine and Jetwash Lost Work

The airplane’s drag lost work (per second) can be evaluated as power over a one second interval per Equation 11 and Equation 12.

$$LW_{airplane\ drag} = 0.5\rho C_D A_{planform} V_X^3; \quad @\ 1s\ interval \quad (11)$$

$$LW_{airplane\ drag} = V_X \sum Drag; \quad @\ 1s\ interval \quad (12)$$

Equation 12 may be used to calculate the lost work of the engine. The engine produces useful power to overcome the sum of resistances and to provide the “on-board-hotel”. Energy losses from engine operation is estimated by equation 7. An example thermal efficiency for a Brayton cycle representation of a jet engine is 33%. A major deviation from the Brayton cycle is the efficiency of jet engine compression and expansion. The multiple stages and sequential impacting of stator blades lead to compression and expansion efficiencies of less than 70% versus 100% efficiency assumed for the Brayton cycle. An approximation used in this analysis is including blade efficiency in the engine thermal efficiency. Equation 13 accounts for engine thermal efficiency in estimating lost work from liquid fuel conversion to propulsion.

$$LW_E \approx \frac{(1-Eff_{Engine})}{Eff_{Engine}} [(D_{v,f} + D_{v,A} + D_P + D_{Vel})V_X + L_H]; \quad @\ 1s\ interval \quad (13)$$

Equation 7 estimates engine lost work where drag losses are in terms of lost work rather than force.

$$LW_E \approx \frac{(1-Eff_{Engine})}{Eff_{Engine}} [(LW_{v,f} + LW_{v,A} + LW_P + LW_{Vel}) + L_H] \quad (F)$$

At steady-state, the lost work of flight dissipates to surrounding air, exiting as gradients of pressure, velocity, and temperature gradients to free stream surroundings. Pressure dissipates at the speed of sound and transforms into velocity within about a vehicle length distance from aircraft as illustrated by pressure contours later in this paper (e.g., Figure 4). Velocity gradients ultimately transform into waste heat including intermediate conversion of more-streamlined flows into turbulence as illustrated by Figure 1. Some work is lost in the form of sound which can propagate for larger distances.

Increasing the reversibility of flight may be considered substantially synonymous with generating minimal impact on the surrounding “free stream” air. Figure 1 illustrate2 jetwash including the dissipation from velocity flows to turbulence which dissipates to waste heat. The ground-effect flight of Figure 1 benefits from the ground blocking downwash losses where a trailing-edge stagnation point transforms downwash to jetwash.

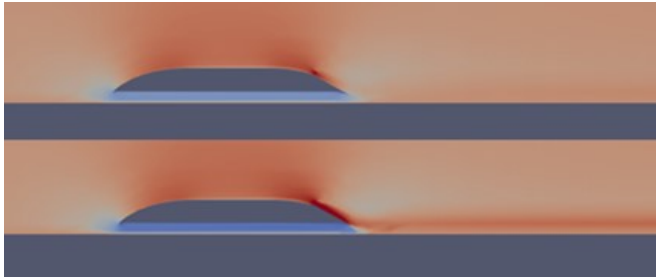


Figure 1. Illustration of jetwash (lower image) behind a ground-effect flight transit vehicle (GEFT) (Suppes, Adam et al. 2025; Suppes, Adam B. et al. 2025a).

An estimate of the jetwash loss starts with equating drag force to thrust force per Equation 14.

$$0.5 \rho C_D A_{Planform} V^2_X = 0.5 \rho C_{D,Wetted} A_{Wetted} V^2_X = \rho A_J U^2_{X,e} \quad (14)$$

Where ρ is air's density, C_D is the drag coefficient, $A_{Planform}$ is planform area, V is aircraft velocity, A_J is cumulative turbojet discharge area, and U is a representative net turbojet discharge velocity ($U=V_e-V_j$). Equation 4 expresses this in terms of the ratio of jet discharge velocity to aircraft velocity.

$$\frac{U}{V} = \left(0.5 C_{D,Wetted} \frac{A_{Wetted}}{A_J} \right)^{0.5} = \left(0.5 C_D \frac{A_{Planform}}{A_J} \right)^{0.5} \quad (15)$$

AI search programs are able to rapidly scan the industry for the values of the variables and parameters for Equation 15, including the following representative (e.g., B737) values: a) turbojet jet blade disc area of 1.81-2.43 m² (per jet), b) planform area for 91-125 m², c) cruising C_D values from 0.015 and 0.035, d) takeoff C_D values from 0.04 to 0.08, e) average discharge air velocity is 400 to 600 meters per second, f) commercial jet cruising speeds of 240 to 270 m/s, g) commercial jet takeoff speeds of 67 to 80 m/s, and h) a total turbojet discharge area at about 45% of the intake area (i.e., converging nozzle design). Also, during takeoff, typical power output of airplane engines are 15% to 30% less than maximum power.

At cruising conditions, the areas (110 / 4.4 / 0.45; $A_{Planform} = 110$, $A_J = 4.4 \cdot 0.45$) and C_D (0.02) yield a ratio of velocities-squared of $F_{Area} = 0.375$. Equation 8 includes F_{Area} to account for the Equation 15 relation between velocities and areas. The factor, F_{Area} , is related to kinetic energy which is proportional to velocity squared, and velocity squared is proportional to the ratio of areas per Equation 15.

When gaining altitude and during takeoff C_D increases from about 0.02 to 0.06, the equation yields F_{Area} values of 0.525 to 0.75. The ratio of net engine discharge velocities to cruising speeds consistent with these numbers.

To provide thrust, the turbojet generates an equal and opposite jetwash momentum with respective lost work in the form of the jetwash's kinetic energy. The kinetic energy in the jetwash degrades to turbulence and then to thermal energy in the air. For accounting purposes, the jetwash lost work includes both the actual lost work in the kinetic energy of the jetwash and the engine inefficiencies since decreases in jetwash decrease the engine inefficiencies corresponding to generating the jetwash. Equation 8 provides a formula for the lost work of jetwash which includes that portion of the engine lost work associated with jetwash generation.

Jetwash Approximation

The jetwash may also be calculated under ideal conditions starting with the Equation 16 equation for ideal propeller propulsion.

$$\eta_{prop} = \frac{2V}{U+V} \quad (16)$$

The efficiency, and respective lost work of jetwash, may be estimated as the one minus the propeller efficiency per Equation 16.

$$LW_{JW} = \frac{(1-\eta_{prop})}{\eta_{prop}} LW_{Airplane\ Resistance} = \frac{U-V}{2V} LW_{Airplane\ Resistance} \quad (17)$$

or

$$LW_{JW} = \frac{U-V}{2V} [(LW_{v,f} + LW_{v,A} + LW_P + LW_{Vel})] \quad (18)$$

When applying a reasonable V for altitude climb, U may be estimated per Equation 19.

$$U = \left(0.5 C_{D,Wetted} \frac{A_{Wetted}}{A_J} \right)^{0.5} V \quad (19)$$

Equation 20 expresses the lost work of jetwash with inclusion of engine inefficiencies associated with generating the jetwash.

$$LW_{JW}^* = \frac{1}{\eta_{prop}} LW_{Airplane\ Resistance} = \frac{U+V}{2V} LW_{Airplane\ Resistance} \quad (20)$$

Downwash Lost Work

To provide changes in altitude, an airliner's turbojet engine generates kinetic energy directly as jetwash and indirectly (i.e., via flaps) to downwash. For an airliner, downwash is necessary to gain altitude corresponding to overcoming gravitational force through the change in altitude. Unlike lift at steady-level flight, lift during altitude change is a force through a vertical distance which leads to the lost work of downwash.

Variables and parameters to estimate energies and forces to control altitude are provided by Table 4. Equation 21 identifies the force to overcome gravity which is used to calculate an energy intensity of 120 Btu/pax-mile for the short haul example of Table 4. A 33% thermal engine efficiency takes the 120 Btu/(passenger-mile) increase in aircraft potential energy to a value to 360. Then, assuming a 1:1 ratio of downwash energy to potential energy results in 720 Btu/(Passenger-mile). This 720 assumes all

potential energy is lost and is still much lower than the Table 1 value of 1320 Btu/(pas-mile) (3470-2150) for the difference between long-haul and short-haul. The numbers imply a further, large source of lost work.

$$m g = \rho A_J (V_e - V_j)^2 = \rho A_J U_{Y,e}^2 \quad (21)$$

Table 4. Basic energy intensity associated with gaining altitude.

Energy	Weight Basis (m)	400 kg per passenger (400-480 kg)
	Altitude Change (h)	10,000 m
	m g h / d (d = 500 km)	78.5 J/(passenger-meter), 120 Btu/(passenger-mile)
	m g h / d (d = 5000 km)	12 Btu/(passenger-mile)
Discharge Velocity	737 Light Load	3,000 to 3,500+ fpm
	737 High Load	1,500 to 2,500 fpm
	Example Case	2500 fpm = 12.7 m/s
	Power = m g V _v ; Energy/sec.	49,800 W (Watts)
	Passengers per 737	200
	Jet discharge area per passenger	0.009 (m ² /passenger) = 2* 2(m ²) * 45% / 200
	$m g = \rho A_J U_{Y,e}^2$ 400 kg, 9.81 m/s ² , 1.29 kg/m ³ , 0.009 (m ² /passenger)	581 m/s (versus maximum discharge velocity reference of 250 to 450 m/s (560 to 1,000 mph) e.g. 70 m/s takeoff resulting in 180-380 m/s

If the turbojets were to discharge velocity downward, a velocity of 581 m/s would be required for vertical takeoff per Table 4, which is considerably more than reported net discharge velocities of 180-380 m/s. The conclusion is that flaps produce a much larger area for downwash than a vertically-oriented jet engine; the flaps make takeoff possible for fixed-wing aircraft but may be augmented by high aircraft pitch at takeoff. Equation 22 identifies a representative transformation.

$$Jetwash \rightarrow PE + Downwash + Dissipation \quad (22)$$

Where **PE** is the potential energy of increased altitude, **Downwash** is the necessary downward momentum required for upward force through a distance, and **Dissipation** are pressure gradients, turbulence, and heat dissipated to the environment. Dissipation includes heat generated from skin friction. This is a functional representation where downwash progressively dissipates as it flows away from the aircraft.

The transformations of Equation 22 occur through the formation of pressure contours on the surface of the aircraft due to aerodynamic interactions. The pressure expands to form downward velocity (i.e., downwash) and the aircraft moves upward. Literally, the lost work of jetwash is used to generate lost work of downwash and mostly lost **PE**. In the accounting process of Table 1, skin friction, pressure drag, and velocity penalties are considered as separate items per Equation 23.

$$LW_{\Delta Alt} \approx Jetwash + PE + Downwash \quad (23)$$

Recognizing that Equation 23 approximates an equality in limits of performance, the lost work per pax-mile can be approximated per Equation 24.

$$LW_{\Delta Alt}^* = \frac{t_{\Delta Alt}}{t_{Total} Eff_{Engine}} \frac{1}{k_{\Delta Alt} k_{EffTJ} k_{CDT_{akoff}} k_{Misc}} LW_{JW,Cruising} \quad ; \text{ per pax-mile basis} \quad (24)$$

The multiple multiplying factors of Equation 24 may be replaced with an overall factor.

$$LW_{\Delta Alt}^* = \frac{t_{\Delta Alt}}{t_{Total} Eff_{Engine}} \frac{1}{k_{Overall}} LW_{JW,Cruising} \quad ; \text{ per pax-mile basis} \quad (25)$$

The primary correction to long-haul versus short-haul is change t_{Total} of Equation J.

Flight Plan Calculations

The following are estimates which are additive for hand calculation of the fuel loading for a 737-300 with a 27000lbs payload (approx 200pax plus bags) [ref

<https://aviation.stackexchange.com/questions/34183/what-is-a-rough-rule-of-thumb-for-calculating-fuel-consumption-in-a-modern-jet>]:

- Climb - 2950lbs / 15mins
- Cruise - 5500lbs/hr
- Descent - 600lbs / 20mins
- Hold - 2650 / 30mins
- Alternate - 1950 / 20mins
- Min arrival fuel - 6300lbs

In the analysis of results, these loadings provide a basis for estimating the amount of potential energy from altitude that is recovered as well as additional loading associated with takeoff and landing methods.

This background provides a starting point of completing the lost work analysis of airliner transit. The Results and Discussion start with identifying parameters for the Background equations which are consistent with observed performance and continue with relating the parameters to fundamental phenomena. A critical analysis identifies approaches to reduce energy intensity including proof-of-concept CFD analyses.

Methods

OpenFOAM CFD software was used to simulate digital prototypes prepared as STL files. The SimpleFOAM solver was used with the RANS k- ω SST turbulence model for converged steady state solutions. Two-dimensional (2D) simulations, referred to as airfoils or sections, are used to identify trends. Unless otherwise reported, the fluid was air at 1 atm pressure, and the free stream velocity was 40 m/s. Pressure contours are presented with blue as low pressures, red as high pressures, and a symmetric scale where 0 gauge pressure is green. Velocity is provided in a different hue blue (zero)-red. Computer aided design (CAD) was used to create STL files by combining common geometries. Methods were matched to maintain fidelity and methods analogous to those within the field [10, 18-21].

For ground effect simulations, the ground was simulated as a lower boundary condition with a velocity equal to the free stream air. Propulsion was simulated as momentum generation through source zones.

Free stream flow boundaries were simulated at a minimum of 10 chord lengths from the vehicle. Meshes were generated with the SnappyHexMesh OpenFOAM function with added boundary layer separation along the section surfaces expanding for 7 layers with 20% expansion to match the overall refinement. Meshes were on the order of 200,000 nodes for 2D and 50,000,000 nodes for 3D simulations with mesh independence testing showing less than 5% deviation in computed results from twice as refined meshes. 2D solutions were converged to pressure residuals of $1e-6$ while 3D solutions were converged to residuals of $1e-4$. The benchmark comparison was to match the conditions of previously published airfoil CFD simulations by the authors which set conditions to appropriately match NACA 0012 [4].

Rectangular cell zones use momentum generation to simulate impellers, ducted fans, or other propulsors. In 2D CFD, no distinction was made between impellers and horizontal-flow ducts while in 3D impellers were simulated as cell zones with a radial distribution of horizontal velocities.

OpenFOAM simulation reports lift and drag coefficients based on the same reference value for area which may be different than the model scale. The data reported in this work are C_L and C_D as calculated by OpenFOAM with a planform reference area of $1m^2$, adjusted by planform area should it differ from $1m^2$. L/D is calculated as the ratio of C_L to C_D .

The lost work analysis was performed through sequential estimates of

Results

Base Case Lost Work Analysis

Preliminary estimates of lost works are provided by Table 5 including initial estimates for the multiple factors included in $F_{Overall}$. The value of occupancy ($F_{Occupancy}$) was increased until the total lost work for long-haul flight matched the long-haul total of Table 1.

Table 5. Preliminary estimate of lost works for airliner transit.

	LW (Btu/(pax-mile))
Fuselage* ($D_{v,f}$)	10.3
Hotel (L_H)	10.3
Appendages ($D_{v,A}$)	10.3
Pressure Drag (D_p)	20.6
Velocity Penalty (P_{vel})	301
Takeoff/Alt (long haul)	438
Jetwash	471
Engine (LW_E)	889
Total (long haul)	2150
Takeoff/Alt (short haul)	1022
Total (short haul)	2738

Table 6. Summary of parameters and intermediate calculations corresponding to Table 5 lost work analysis.

Parameter			units		C_D	
$t_{total, shorthaul}$	1.5	hr			Fuselage*	0.000921
$t_{total, longhaul}$	3.5	hr			Appendages	0.000921
	400	kg/pax			Pressure Drag	0.001842
		$m^2 /$				
A_{wetted}	1.5	pax			Sum C_D	0.003684
		$m^2 /$				
$A_{TJ-Disc}$	0.0009	pax				
$A_{wetted} / A_{TJ-Disc}$	1666.667				k	
$C_{D-Wetted} / D_{v,f}$	0.000921				k_{Alt}	1.75
$k_{Occupancy}$	1.475				k_{TJ-Eff}	3.5
$D_{v,f}$ base case	7				k_{Misc}	2.0
$D_{v,f}$ railcar	19				$k_{Vel,takeoff}$	4.0
t_{Alt}	0.25	hr			$k_{Overall} (calc)$	49.0
Eff_{Engine}	0.33					
Fuel Penalty	N/A				$k_{Vel,cruise}$	7.3
V (cruising, input)	520	mph			k_v to appendage drag	1
U (calc.)	911	mph			k_v to pressure drag	1

A preliminary finding of Table 1 is that jetwash and downwash losses can readily exceed lost works of liquid fuel engines when the inefficiencies of the engine related to the jetwash and downwash are included in the jetwash and downwash terms. To improve conversion of estimates to agree with both long-haul and short-haul estimates requires a more in-depth analysis of the multiplying factors which will be part of the Discussion.

The high value of lost work associated with runway takeoff and use of flaps to achieve downwash for climb identifies the opportunity for improved approaches to these processes. The subsequent results focus on proof-of-concept for a lifting-body approach to takeoff and climb that avoids the use of wing flaps.

CFD Studies of Downwash

Figure 2 compares downward air flow through three configurations of a bell nozzle: a) an upper fan, b) lower fans directing flow horizontally above a plate, and c) lower fans directing flow horizontally and downward in a basket configuration. The CFD meshes illustrate the geometries with pressure and velocity profile results presented in Paraview. The simulation results of Figure 2 validate the hypothesis that horizontal flow impacts walls of a lifting body cavity which generates pressures on the lower surface of the bell nozzle and creates a broader downwash of lower average velocity.

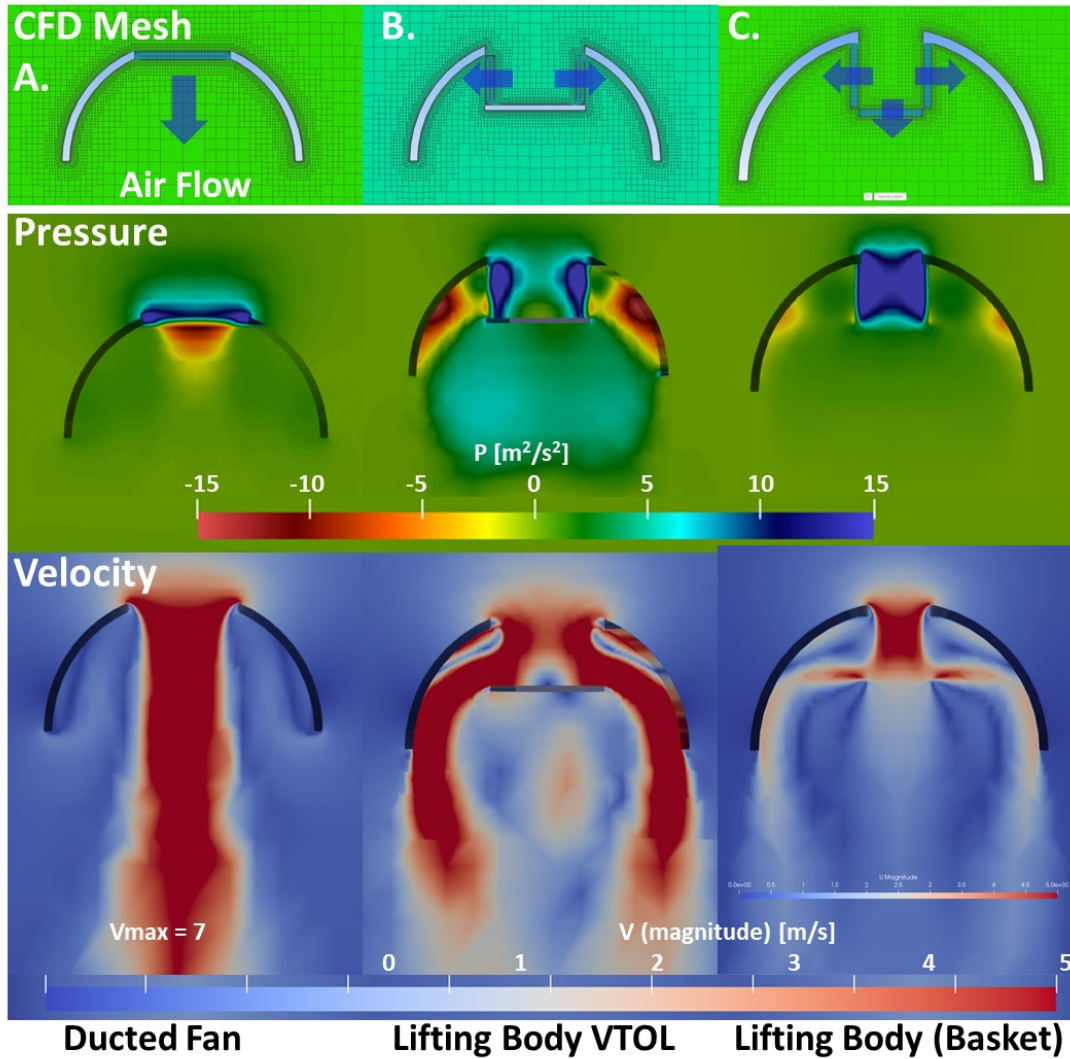


Figure 2. CDF section (2D) simulation results of flow through a vertical duct/orifice into a lower bell nozzle with: a) Ducted Fan: a fan accelerating air downward, b) Lifting Body: a Source accelerating air horizontally outward from below the orifice, and c) Lifting Body: a Source accelerating air horizontally outward below the orifice while maintaining some permeability in the source plate.

The Figure 2 approach is a diverging nozzle design where the vehicle surface is a nozzle surface and horizontal flow air movers (e.g. a centrifugal impeller) are used to control the pressure contours.

3D simulations of Figure 3 were consistent with the Figure 2 two-dimensional (2D) simulations, generating similar pressure profiles for the ducted fan and the lifting body with respective aspects of performance. The qualitative differences are minor, and any choking of flow can be addressed by design degrees of freedom such as the size of the upper orifice, use of an additional fan in the upper orifice, optimization of surface morphology, and impeller design.

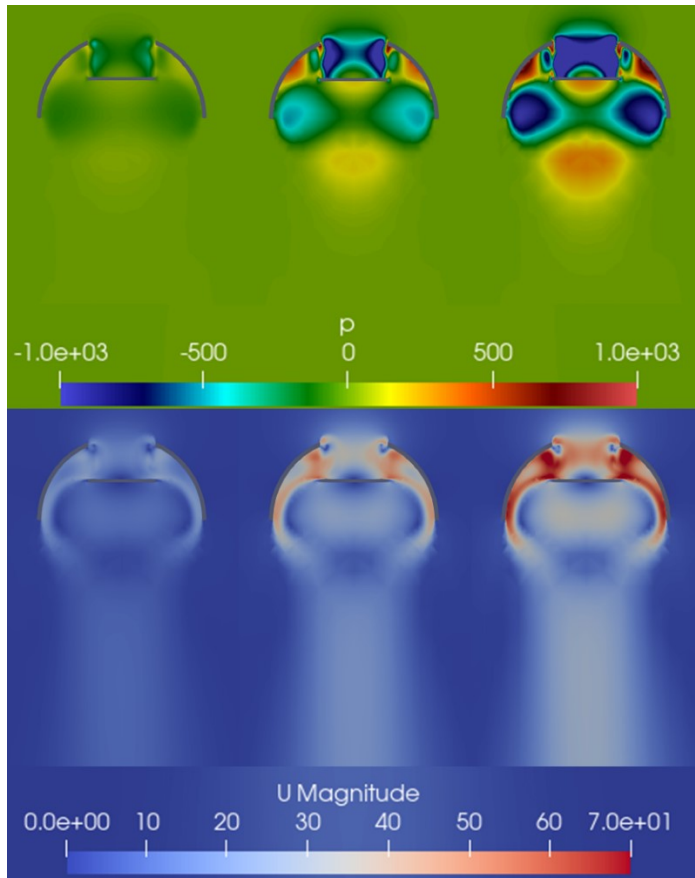


Figure 3. 3D CFD simulation results of pressure (top) and velocity (bottom) contours for impeller flow onto a bell nozzle. Momentum generation through the impeller are 5 (left), 25 (middle), and 50 (right) m^4/s^2 .

Figure 2c presents a modified version of the vertical impeller (“basket impeller”) for greater efficiency with pressure and velocity acting on broader areas. The basket impeller incorporates a lower-surface fan rather than the impermeable plate of Figure 2b. In a basket configuration, lift from the bottom fan of the basket is transmitted through a shaft of rotation rather than pressures on lower surfaces of the body.

Figure 4 illustrates an approach where additional surfaces are incorporated into the diverging nozzle design. The additional vertical surfaces may be referred to as vertical stagnation plates and are basically a design degree of freedom to meet an objective of a nearly-constant vertical component of pressure force on a lower surface for lift or a nearly-constant horizontal component of pressure force on aft surfaces for thrust.

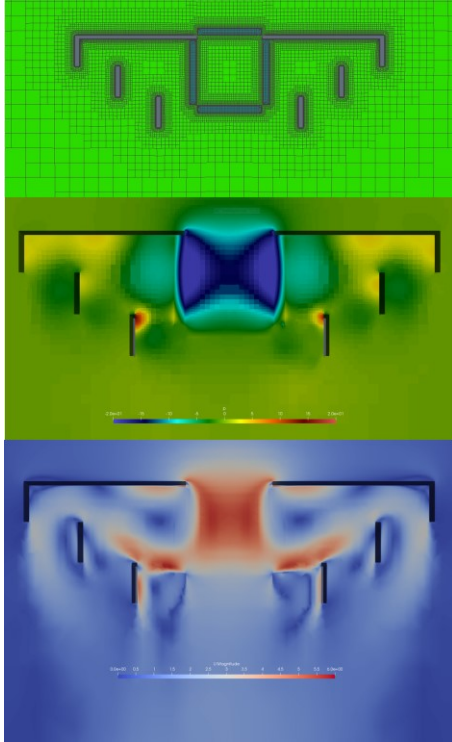


Figure 4. 3D CFD simulation illustrating impact of vertical surfaces on ability to generate downward flow of air and respective more-even vertical components of pressures.

Discussion

The CFD results identify that the fan and horizontal sources are able to generate increased pressures in a lower cavity of a lifting body versus a “pressure disc” commonly associated with the shaft-transmitted lift of rotary wings (i.e., helicopters) and tilt ducts [22-25]. Within a bell nozzle lifting body, higher pressures rapidly expand to form downward velocities. The findings can be summarized through forms of thermodynamically allowed (i.e., spontaneous) energy transformations from either velocity or pressures.

Velocity may convert to turbulence which dissipates as heat waste, including through boundary layer separation and respective dissipation. Air flow may collide with surfaces and transform to pressure. Air flow may also collide with other air flow or stagnation points to form higher pressures. High pressure, relative to freestream flow, can expand away from surfaces in a transformation from enthalpy to kinetic energy. The enthalpy of an ideal gas is only a function of temperature; however, the ideal process of isentropic adiabatic compression results in increased temperature of the gas. The accepted open-system thermodynamic accounting of the energy placed into the gas is the energy due to temperature change as a result of isentropic-adiabatic compression or expansion.

Pressure expands away from surfaces near the speed of sound and mixes with surrounding air as confined by surfaces such as a duct, bell, or vehicle frame. The expansion will mix with airflow and may be transformed into turbulent or non-turbulent flow. The conditions leading to laminar vs turbulent flow continue to be an active, high interest research topic in the field of aviation.

The previous paragraphs on spontaneous transformations are a practical extension of the Three Principles of an airfoil science described elsewhere [3].

Principle 1. Impacting air creates higher pressures which are illustrated by the higher pressures (i.e., stagnation points) at leading and trailing edges; the air flow creates pressure when impacting surfaces, regions of high pressure (e.g., leading stagnation point), and air flow at different velocity vectors (e.g., trailing stagnation point).

Principle 2. Diverging air creates lower pressures.

Principle 3. Air expands from higher to lower pressure at the speed of sound; changes in an airfoil's trailing section affect the pressure throughout the airfoil.

This work applies the principles to impeller and fan designs to generate horizontal flow and with heuristic guidance of Equations 3 and 7 to design a more efficient VTOL. Discussions of this paper treat the dynamic pressure of air's velocity and static pressure as inter-changeable per $P = 0.5 \rho U^2$. The resulting kinetic energy is largely preserved until the velocity transforms into turbulent flow (i.e., boundary layer separation), leaves the proximity of a vehicle as jetwash or downwash, or dissipates to heat in viscous skin-friction losses.

Multiple advantages of lifting-body VTOL designs arise. The utilization of a narrow duct through the fuselage offers less interference with overall functionality. Unlike rotary wing and helicopter designs, there is no direct downward impact of air on the upper surfaces of the fuselage or wings. The design transforms most of the lower surface into a lifting body, utilizing commonly present planform areas as lifting bodies without additional costs and drag from rotary wings or tilt-wing ducts. The design maintains a simple structure to minimize the amount of moving components, increasing robustness.

The underlying physics and respective equations allow for comparison to estimate potential energy efficiency, particularly within the air taxi field. For example, air taxi designs with lift-generating blades that have a low area relative to vehicle planform area will tend to have low flight efficiencies.

Observed Lost Work

Figures 2 and 3 qualitatively illustrate lost work in the form of downwash, which is particularly evident by in Figure 2a where the downwash stream leaves the immediate surroundings of the airfoil and transforms into turbulence then waste heat. The visual presentation of velocity provides illustrative data of downwash as a form of lost work as quantitatively described in equation 7.

Equation 9 quantifies the lost work from downwash where the 0.5 factor for the lifting body is doubled to account for the ability to generate lift forces on the upper surface as well as the lower surface.

$$\frac{LW_{LB}}{LW_{DF}} = \frac{\rho A_{LB} U_{Y,LB}^2}{\rho A_{DF} U_{Y,DF}^2}, \text{ or } \frac{U_{Y,LB}}{U_{Y,DF}} = \sqrt{\frac{A_{DF}}{A_{LB}}} \quad (9)$$

Equation 9 identifies that when the lifting body surface area is larger than the duct area, the lifting body can have less lost work and correspondingly increased efficiency. Increased efficiency would be due to lower downwash velocities containing lower total lost work. For a circular perimeter, a 44% increase in radius doubles the efficiency in the ideal limit; the relative dimensions of the bell and eye of the impeller (50:10.7) of Figure 2c identify a 3.7-fold $((50/10.7) - 1)$ increase in efficiency.

For ground effect flight with a small lower-cavity perimeter gap, Equation 10 approximates lost work relative to free flight. Since the same cavity pressure leads approximately to the same velocity of air exiting from the cavity as dissipates from free flight downwash.

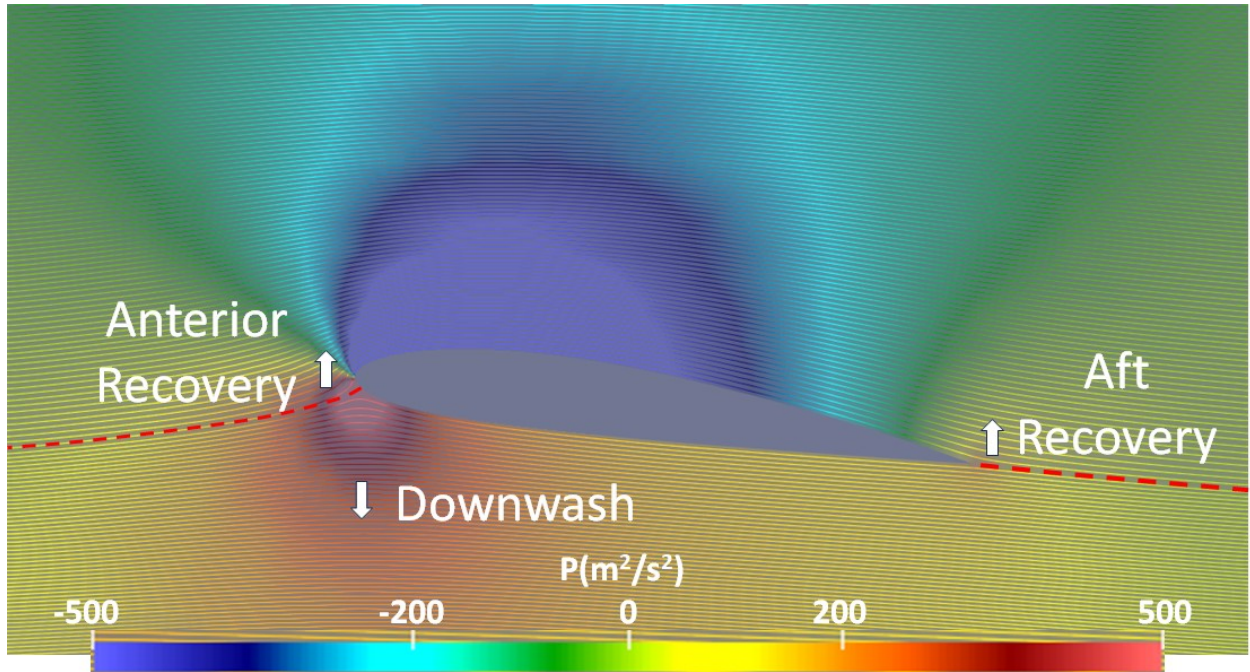
$$\frac{LW_{GE}}{LW_{LB}} \approx \frac{A_{Gap}}{A_{LB}} \quad \text{when} \quad \frac{A_{Gap}}{A_{LB}} \ll 1 \quad (10)$$

Therefore, in the limit of the gap of the cavity perimeter reaching zero, the lost work for ground effect flight goes to zero. This is why greater efficiencies are possible in ground effect flight and conversely, the efficiency increases with decreasing clearance (i.e. gap) as less outlet area leads to less flow which leads to less lost work. As A_{Gap} increases, the lost work of the ground effect flight approaches the lost work of the lifting body for hovering.

Use of centrifugal impellers can transform the lower cavity of a ground-effect flight vehicle to a lifting body surface for vertical takeoff. The underlying mechanisms create a foundation for improving the efficiency and free flight capabilities of ground-effect flight transit (GEFT) which utilize both lifting body designs and the anterior recovery mechanisms discussed in the following paragraphs.

Rotary Wings and Steady-Level Flight

Higher pressures on the lower surfaces of airfoils expand downward and horizontally, potentially creating downward velocity and lost work; however, decades of studies and data identify that fixed wings achieve lift at much higher energy efficiencies than shaft-based lift. Figure 5 illustrates a typical pressure profile which develops on NACA-type airfoils.



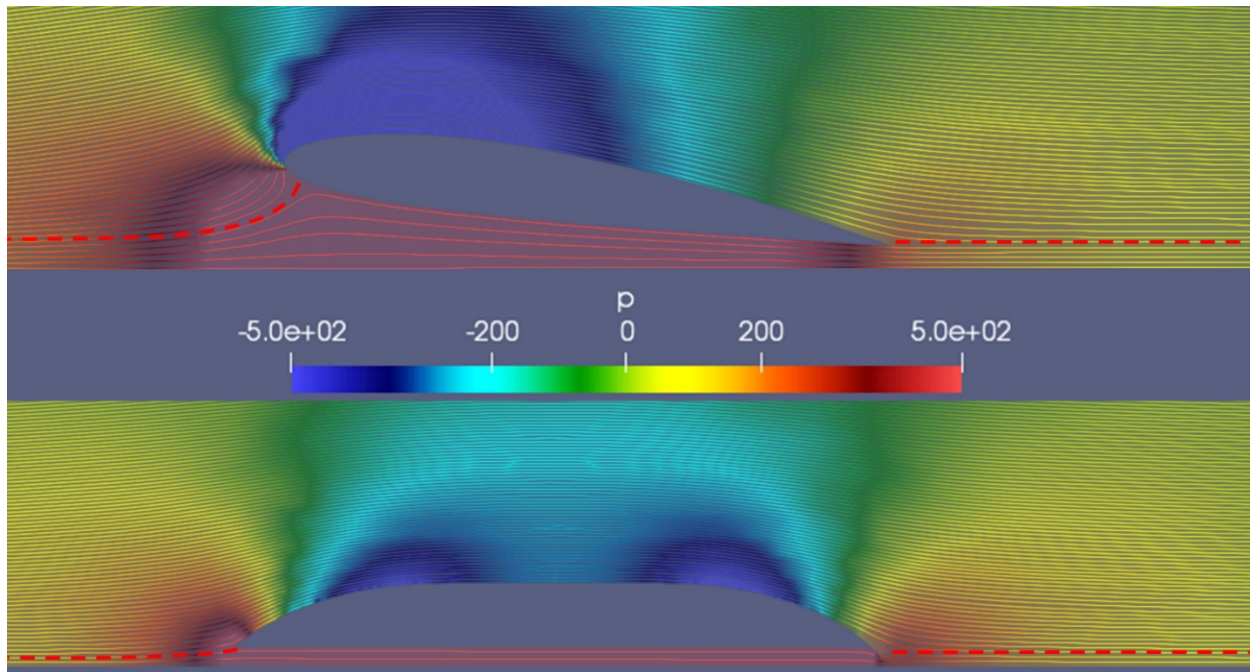


Figure 5. Illustration of pressure recovery superimposed over a flow streamline image for a NACA airfoil and ground effect flight transit vehicle.

Lift on an airfoil can be quantified as the vertical component of the surface integral of pressures. Unlike the Figure 2 models, the NACA and GEFT airfoils of Figure 5 generate negligible downwash. Rather than lower pressures manifesting as downwash, the surfaces of the Figure 5 airfoils generate leading edge stagnation points with high pressure gradients driving pressure expansion upward in competition with downward expansion.

To quantify the rate of anterior recovery of pressure versus downward dissipation of pressure, pressure gradients were extracted from CFD simulation results. The pressure gradients for upward expansion were 625,000 and 28,000 m/s^2 , which results in units of Pa/m when multiplied by air's density. This calculates as a cumulative flux of $1.0 \times 10^5 \text{ m}^2/\text{s}^2$ vertically. The downward expansion was 930 m/s^2 acting over 0.108 m, for a downward flux of 101 m^2/s^2 . The anterior recovery flux is about 100-fold the downward flux due to the extreme pressure gradient at the leading edge. These estimates and the visual presentation of pressure gradients by Figure 5 identify that anterior recovery of lift pressure can be much greater than downward dissipation of lost work. Leading edge stagnation points with high pressure gradients are common observations on NACA-type airfoil pressure contours in literature.

Analogous to an ideal thermodynamic heat engine cycle, air may compress and expand in near-reversible processes. In the case of airfoils, avoiding the formation of downwash or jetwash avoids a primary mechanism for generating lost work. In ground-effect flight, the ground blocks downward pressure dissipation leading to higher flight efficiency. Under optimal conditions, leading-edge and trailing-edge stagnation points merge to form high pressures under the airfoil at static pressures near air's relative dynamic pressure. Aft recovery may occur through a trailing-edge stagnation point, but the pressure gradients are low compared to the leading edge. In free flight, the aft recover is low compared to anterior recovery.

Despite existing in front of the wing, the anterior recovery step is a recovery of pressure generated by the wing. This response is possible because pressure expands, against oncoming airflow, at the speed of sound. The data of Figure 5 are at 40 m/s as compared to the speed of sound at about 340 m/s.

In the fully reversible limit of performance, the streamlines and velocity profiles behind the airfoil are similar to those in front of the airfoil which is increasingly the case for ground-effect flight.

The overhead rotors of helicopters are commonly referred to as rotary wings rather than blades. Well-designed rotary wings realize anterior recovery and tend to be more efficient than tilt-ducts for hovering and vertical takeoff vehicles. A downwash of a rotary wing, as necessary to increase altitude generates higher pressures on the upper surfaces of a helicopter fuselage to the disadvantage of helicopters relative to lifting body designs. Lift generation by rotary wings requires much larger diameters of rotation than ducted fans with ducts passing through fuselages or wings.

Stagnation Plates

As identified by the anterior recovery mechanism, pressure can expand over edges to generate lift via more-reversible mechanisms than through downwash. Since pressure expands much faster than aircraft takeoff velocities, a hypothesis emerges that free stream velocity is not necessary for anterior recovery.

Figure 6 illustrates preliminary designs and pressure contours of a bell nozzle using radially-inward suction pressures on the upper surface and radially-outward air flow on the lower surface. Approaches A-B failed to generate lower pressures on the upper surface except immediately by the intake. Increasing the size of a plate above the impeller had minimal impact.

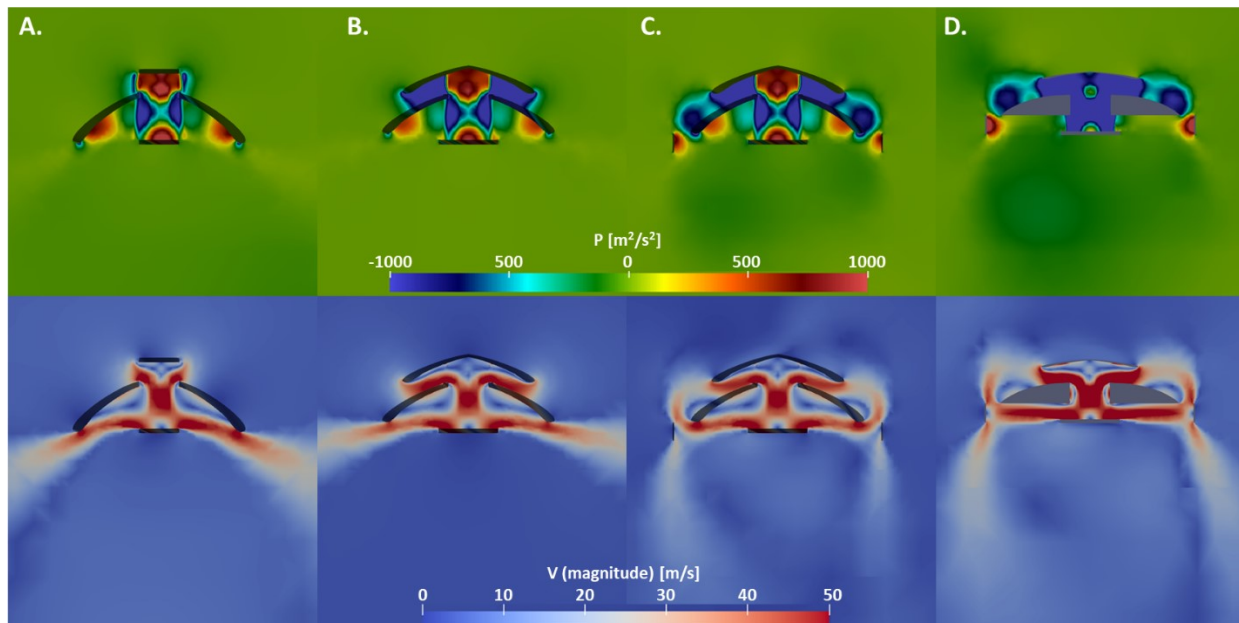


Figure 6. Pressure and velocity contours of alternative designs to reduce downwash and generate lifting body forces through recovery by inducing horizontal flow on upper and lower surfaces with: A. A small upper plate, B. A larger upper plate and lower curvature central plates, C. Vertical stagnation plates, and D. An alternative geometry with vertical stagnation plates.

A further hypothesis arises that stagnation points may be necessary for effective recovery and that vertical plates may be used to generate stagnation points. Figure 6C illustrates the impact of adding vertical stagnation plates adjacent to the bell nozzle's perimeter to the Figure 6B design. Air flow generated by the lower propulsor impacts the plate, generating a higher-pressure region similar to a leading-edge stagnation point. The conditions develop greater upward air flow than downward flow. The Figure 6c contours validate the concept and approach for the development of anterior recovery without lateral translation.

Figure 6D expands upon the illustration of anterior recovery by replacing nozzle bell's lower concave surface with a flat surface. The change in geometry fails to substantially improve performance but does illustrate how propulsors and stagnation plates provide valuable degrees of freedom for pressure contour engineering. Thin vertical stagnation plates are a base case and proof of concept.

Horizontal stagnation plates may create similar dynamics to convert vertical airflow into induced thrust on aerial vehicles which often decreases both lift and drag. Commercial aircraft cruise at the lower pressures of higher altitudes to reduce drag and lift. Similar cruising speeds at lower altitudes would generate too much lift and high drag, preventing steady state cruising conditions. Alternative approaches are needed for highspeed flight (e.g., 400 mph) at lower altitudes as consistent with ground effect flight, air taxis, drones, and helicopters.

The pressure contours of Figure 7 validate the use of a horizontal stagnation plate. Similar to the vertical stagnation plate of Figure 6, the horizontal stagnation plate creates an improved pressure profile by using at stagnation point to re-direct air's flow direction. The base case plate has minimal negative impact on drag due to a low frontal projection; however, by inducing a stagnation point behind and above the trailing edge, induced thrust is generated due to higher pressures are expressed on the trailing taper. Lift is reduced due to higher pressures pushing down on the plate.

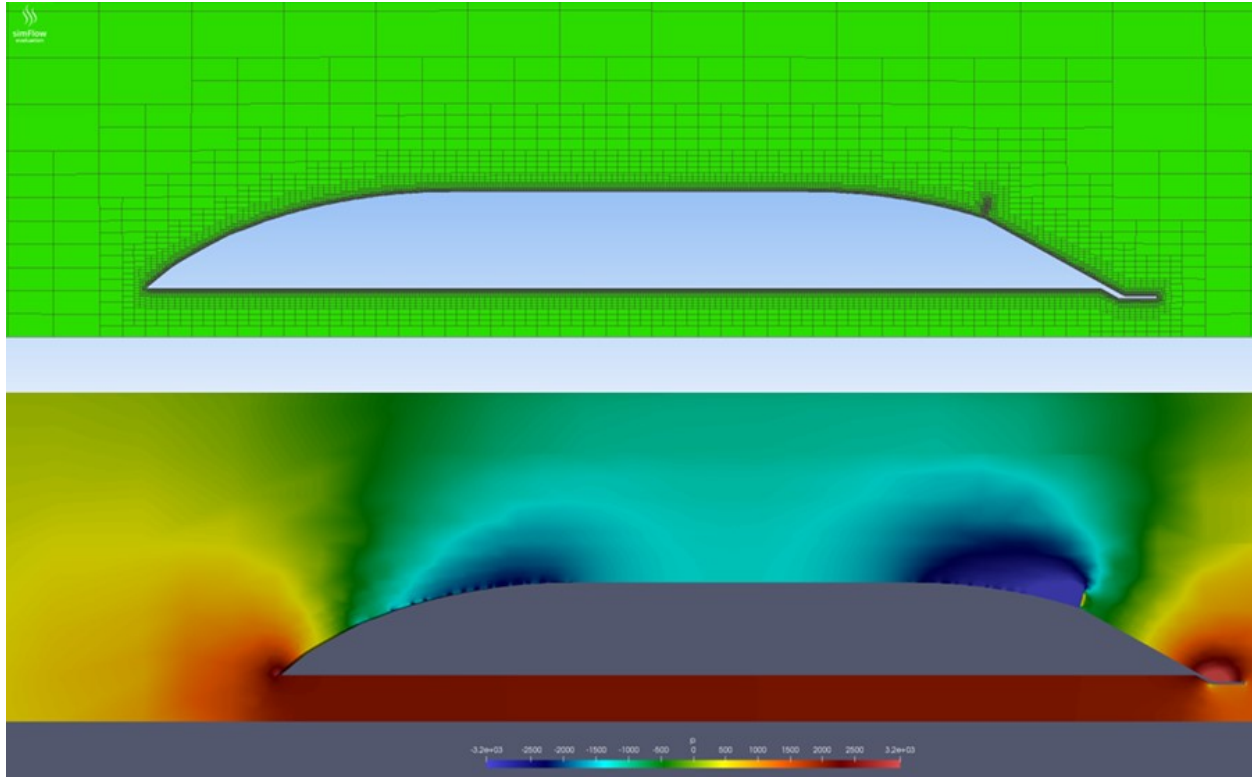


Figure 7. Pressure contour illustrating horizontal stagnation plate behind trailing edge. Settings include free stream velocity of 80 m/s and propulsor horizontal and vertical settings of 12 and -8 m⁴/s².

The upper speeds of helicopters and hybrid vertical takeoff vehicles also remain limited by inherent high drag [1, 26, 27]. Alternative lifting body vertical takeoff designs may incorporate stagnation plates to both increase lift for vertical takeoff and decrease drag for higher-speed cruising.

Pressure Contour Engineering

Principles 1-3 are consistent with the molecular theory of gases which: a) distinguishes between pressure expansion and velocity flow, b) identifies how the collision of air flow with a surface is a molecular steady-state phenomena, and c) associates “no-slip” condition for viscous flow on surfaces as a result of gas molecules departing from surfaces in random directions despite collisions which may have a direction of flow [3]. These principles are identified based on CFD calculations based on the Navier-Stokes equations through the lens of a macroscopic scale to innovate and develop and continuously improving understanding based on a fundamentally correct foundation. When applied to CFD, the RANS (Reynold’s-Averaged Navier Stokes) introduces minimal error on the applications of primary interest, primarily introducing errors related to force magnitudes [21, 28].

For propeller-based lift and thrust, the force is transmitted through a rotating shaft; they are shaft-based thrust and lift devices. For rockets, significant thrust is transmitted to a bell nozzle which is a nozzle contoured to simultaneously receive lift forces and direct gas flow to maximize those lift forces. The bell nozzle is a form of pressure contour engineering. Figures 2 and 3 illustrate an approach to transform air flow through a vertical duct from shaft-based lift to pressure contour engineering for generating lifting-body lift.

The broader topic of propulsors and ducts as a design degree of freedom to generate lift and reduce drag has the potential to transform mobility by substantially increasing energy efficiency. Preliminary work has substantial validation data for ideal lost work analysis. Follow up work presents a finding that the pressure contour engineering creates “induced thrust” to substantially increase energy efficiency at transit velocities [29]. Both lifting-body vertical takeoff/hovering lift and induced thrust are forms of pressure contour engineering. Benefits of lifting-body vertical takeoff lift versus shaft-based lift include reduced energy consumption, smaller motors, and simpler designs.

The use of propulsors as a targeted design degree of freedom for contour engineering is a substantially new frontier supplementing established pressure-contour engineering to increase L/D of airfoils and streamline fuselages. The Three Principles accurately describe performances of decades of data on airfoil designs, and the consistency of these principles with the pressure contours provides additional validation.

The approach to aerodynamics through pressure contour engineering and CFD governed by Navier-Stokes equations is an attempt to advance vehicle designs with an understanding that does not rely on the underlying assumptions from varied aerodynamic theories of lift. Newton’s second and third laws are considered applicable and have been used in the equation derivations for momentum-based lift. Newton’s laws apply to downwash, which is necessary to increase altitude but minimized with anterior recovery. Theories of lift like Bernoulli’s Theory of Lift and the Coanda Effect have been repeatedly documented as primarily correlations with limited value in design. Of the many “theories of lift,” lifting line theory has prevailed as usefully accurate in both correlation and extrapolation without any widely identified false basis or assumptions.

Lifting line theory introduces the concept that a vortex is attached to a thin wing surface, which can be difficult to comprehend. Figure 5 illustrates how air flow with an optimal lifting body design generates leading-edge and trailing-edge stagnation points. The stagnation points could be perceived as being “attached” to the surface.

Lifting line theory does not teach toward optimal wing section morphology; rather, it teaches toward planforms that provide better lift-drag ratio (L/D) efficiencies. Alternatively, molecular dynamics explains the cause of the leading-edge and trailing-edge stagnation points. Conceptually, the Three Principles could be considered a kinetic-theory-of-gases theory of flight. The Navier-Stokes equations quantify results in numerical method solutions and the Three Principles/kinetic-theory-of-gases theory of flight assist in understanding, extrapolation, and innovation.

Anterior recovery is presented as an accurate, fundamental physics-based explanation of how fixed wings lead to more efficient flight than momentum-based lift and identification of similarities complementing lifting line theory. The ability to collaborate lifting-line theory methods while identifying differences in lifting-line theory derivation is a validation of the approach for the present work. If vortex flow is interpreted as air flow initiating on lower surfaces and terminating upper surfaces, the vortex flow accelerates lost work generation. Anterior recovery is pressure expansion rather than air flow.

Diverging Nozzle Lifting-Body Fuselage Designs

Use of diverging nozzles for subsonic commercial airliner applications is a substantial deviation from standard approaches where converging nozzles are the norm. Two significant benefits emerge from use of diverging nozzle approaches:

- Increased energy efficiency
- Ability to use smaller ducts for routing propulsor/thruster air flow through fuselages.

Figure 8 illustrates a fuselage design with an internal duct network which with entrances at fuselage locations where lower pressures are designed and discharges as diverging nozzles for operation over a range of thrust and lift configurations. The ducts have significantly smaller cross sections than the planform and vertical profiles of the lift and thrust surfaces.

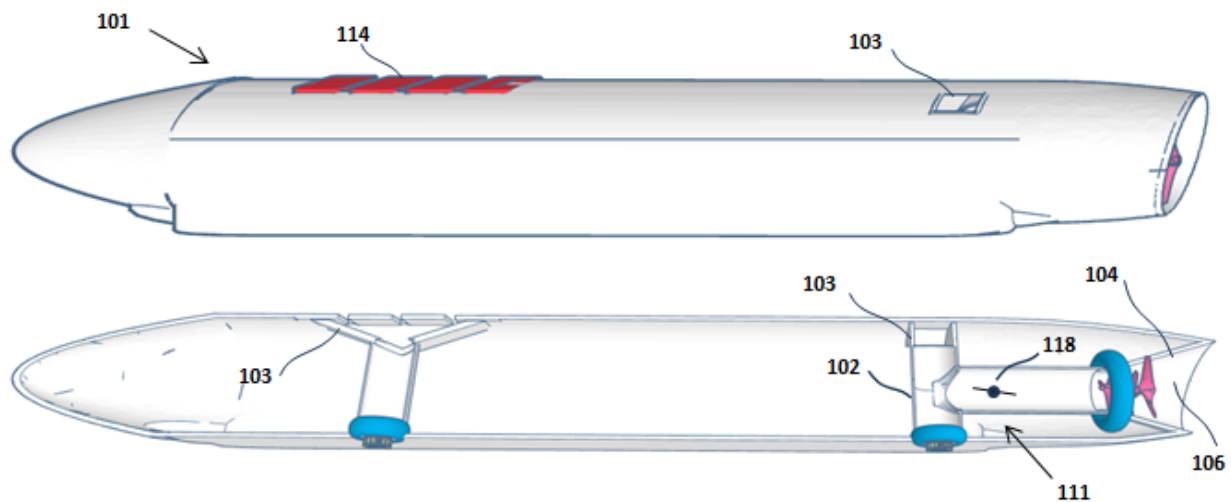


Figure 8. Example fuselage design incorporating an internal duct network and diverging nozzle discharges. The air blower on the lower surface creates horizontal air flow including impact of air with fences on the sides of the lower surface.

Electric motors are preferred for the Figure 8 design. Turbofans driven by electric motors at duct entrances (not shown) may be used to increase air pressure to reduce duct cross sections.

The inconvenience of internal duct networks varies based on application where it can be easily overcome for drones and routing of ducts can allow access consistent with passenger transit. This approach can reduce most of the lost work associated with alternative approaches using wing flaps to generate downwash. Additional ducts may be incorporated to provide pitch, roll, and yaw control.

Furthermore, the design can displace the use of wings, external wings, and vertical/horizontal stabilizers. Designs emerge with substantially reduced drag associated with appendages which reduces wetted surface areas, pressure drag, viscous drag, and respective jetwash. The implication is that >90% reductions in energy intensity are possible when these reductions in lost energy are used with battery power.

Technology resulting in a 90% reduction in energy intensity qualifies as a disruptive technology. The designs allow air transit at energy efficiencies comparable to the ground-effect flight railcar of Table 1. Batteries emerge as a primary cost and limitation of electric aircraft which translates to this technology substantially reducing costs of electric aircraft.

Energy intensity at cruising conditions would reduce by about 70% rather than 90%. A 70% reduction in energy intensity allows electric motors to achieve higher speeds. Also, multiple electric motors can be incorporated in ducts to both increase power and redundancy/safety.

An important aspect of the Figure 8 design is scalability with applications from small drones to ships larger than aircraft carriers. This scalability does not apply to the ground-effect flight railcar of Table 1, since a critical performance parameter is the ratio of gap area to planform area, where reducing gap area to very low levels can be problematic. Large wings are not necessary for the Figure 8 design, but smaller wings can be advantageous for certain applications.

Designs merge free flight aircraft may be compatible for multi-modal transit on land corridors which implies the emergence of flying car concepts that are energy efficient, fast, and practical. For multi-modal vehicles free flight over cities may not be optimal, however, low-altitude designated flight corridors that connect ground transit corridors can be advantageous.

Critical Thinking on Downwash Lost Work

The preliminary lost work analysis of Table 5 identifies that lost work associated with takeoff and increasing altitude as a major source of lost work which becomes the prominent source of lost work for short-haul flights. A preliminary ranking of causes of this lost work contributing to k_{Overall} consists of:

- ($k_{\text{TJ-eff}}$) As propulsor discharge velocity increases, propulsor efficiency decreases per the Equation 17 estimate.
- (k_{Alt}) Use of jetwash (lost work) to generate downwash (lost work), via wing flaps, essentially doubles aspects of lost versus direct generation of downwash.
- (k_{Misc}) Accounts for additional fuel use associated with runway takeoff and landing such as: a) hold pattern fuel and b) taxiing fuel.
- ($k_{\text{Vel,takeoff}}$) Accounts for the impact of velocity and pressure on drag, but a value of 4 is less than the Table 1 value of 7 used for cruising at 540 mph.

Also, the preliminary analysis also identifies that estimates of the lost work associated with takeoff and increasing altitude as being under-estimated with a short-haul total of 2738 Btu/(pax-mile) compared to the Table 1 reported value of 3470 Btu/(pax-mile). An application of the fuel loading numbers of the Background is consistent with more lost work associated with reliance on runways and use of wing flaps for climb.

Future Work

The CFD methods of this paper enable rapid evolution of new designs, particularly designs based on pressure contour engineering. Ongoing and future work focusses on contour engineering to identify designs with lower engine and energy storage costs to reduce the costs of subsequent detailed CFD studies and prototyping. Parallel work developed ideal flight mechanisms, similar to ideal heat engines, to further expedite identifying lower cost and higher-performing designs [29].

Work continues on the critical analysis of the factors contributing to k_{Overall} . This work merges separate approaches for estimating drag, estimating efficiencies, and estimating fuel loading (which can be related to lost work). This merging requires an extended effort beyond the proof of concept of this paper.

Conclusions:

Lifting body vertical takeoff designs were simulated utilizing the full planform area for lift efficiency advantages. The approach includes increased vertical takeoff efficiency due to decreased average velocity in the downwash through the use of a larger surface area for the lift pressures to act upon. For simulation of lifting-body forces on a bell-nozzle lifting body, the transformation between dynamic pressure in air flow and static pressure on surfaces initially transforms horizontal air flow to lift pressures in the lower cavity and then lift pressures to downwash.

Downwash is necessary lost work for vertical takeoff altitude changes, but downwash at static altitude typically fully transforms into lost work. Lifting-body lift results in increased efficiency versus the shaft-based lift of vertical ducts as lower downwash velocities are generated by the lifting-body area which can be consistently larger than the pressure disc of a ducted fan. Fixed-wings and rotary wings are considerably more efficient than shaft-based lift approaches due to anterior recovery which recovers lift pressures rather than allowing pressures to dissipate downward.

The engineering of pressures on fuselage surfaces is part of a broader topic of pressure contour engineering, which has the prospect to substantially increase thrust and lift efficiencies by decreasing lost work from jetwash and downwash. Pressure profiles provide qualitative verification of vertical and horizontal stagnation plates to create lifting-body lift and reduced drag, respectively.

The proof-of-concept for >90% reductions in energy intensity of air transit is presented from the perspective of identifying sources of lost work that can be mitigated, including lost work due to: a) use of flaps to generate downwash, b) use of converging nozzle designs that increase lost work versus a new diverging-nozzle design, and c) switching from heat engine to battery power. The proof-of-concept includes a base case design using a duct network and a fuselage with thrusting and lifting body surfaces.

List of Symbols

η	Efficiency
ρ	Density (air at 1.29 kg/m ³)
A	Area
C	Coefficient (L for lift, D for drag)
D	Drag
Eff	Efficiency
Force	Force
k	Multiplying Factor/Parameter, Specific to subscript
L	Load
LB	lifting body
LW	Lost Work
m	mass
prop	Propeller, blade, or turbine
P	Pressure
t	time
U	velocity (air)
V	Vehicle velocity
W	Work
X	Cartesian Dimension, horizontal direction of vehicle travel
Y	Dimension, vertical
Z	Dimension, horizontal spanwise from vehicle

*	(superscript) Includes related engine inefficiencies
A	(subscript) appendage
D	(subscript) Drag
DW	(subscript) Downwash
e	(subscript) exit
E	(subscript) engine
f	(subscript) fuselage
H	(subscript) Hotel
JW	(subscript) Jetwash
L	(subscript) Lift
O	(subscript) free stream
P	(subscript) pressure
v	(subscript) viscous (skin friction)
Vel	(subscript) velocity

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Supplement

Design and Engineering of Lifting-Body VTOL:

Advantages of Lifting Body VTOL - Advantages of the presented lifting body VTOL approach include:

- The approach is able to maximize the lift area relative to other ducted fan approaches.
- avoids the destructive interference of downwash from rotary wings with paths of travel over the fuselage, arms, and wings.
- is especially compatible with ground effect flight (e.g., over waterways, highways, railways, and open range) with efficiencies tenfold that of helicopters.
- allows greater ground clearances while maintaining robust lift for ground effect vehicles.
- provides a minimum footprint for access to a wider range of landing sites and a smaller target for disruption of flight.
- enables extreme lifting-body cruising aircraft to have low drag due to absence of wings needed for takeoff and lower velocities in the absence of augmented lift.
- enables smaller ducts through fuselages to achieve higher lifts than otherwise possible.
- is relatively simple and low cost, especially relative to the swashplates of helicopters.
- is scalable in application, ranging from a lower cost version of DJI drones to ships the size of aircraft carriers; this can substantially reduce R&D costs for high-impact technology.
- is inherently robust and compatible with methods for morphing surfaces to expand and contract to enable greater lift.
- removes rotating blades from traffic of loading and unloading operations.
- forms a foundation for pressure contour engineering as an improved approach to vehicle design.

Design Degrees of Freedom – CFD of relatively simple digital models demonstrate the concept that horizontal flow within a cavity can be used to transform lower vehicle surfaces into lifting body surfaces. The many design degrees of freedom to optimize this objective include:

- duct sizes, shapes, locations, and orientations,
- the use of horizontal flow induction on lower surfaces horizontally away from a duct,
- the use of horizontal flow induction on upper surfaces perpendicular to a duct,
- different horizontal propulsor types, sizes, and locations including impeller propulsors as well as horizontally oriented propellers and fans,
- augmented horizontal flow with vertical flow (e.g., Figure 1c), including use of “basket” impellers with optimal combinations of vertical and horizontal flow,
- the morphology of lower surfaces to generate higher pressures from flow away from duct exits,
- the morphology of upper surfaces to generate lower pressures from flow towards duct intakes,
- baffles, flaps, ducts, and orifices to direct pressures in ducts and cavities toward producing propulsion,
- the quantity and location of ducts; merging and diverging ducts strategically intersecting surfaces to mitigate boundary layer separation, and
- vehicle body transformations between vertical takeoff/landing to free flight to maximize efficiency and robustness throughout flight.

Foremost in new design degrees of freedom are use of: a) propulsors to assist pressure contour engineering toward an objective of minimum lost work, b) ducts in combination with horizontal flow vectoring to increase lifting body forces, c) combinations of the two to achieve objectives without increasing vehicular frontal projection, and d) improved understanding of how ground-effect increases lift-drag ratio efficiency. Initial digital prototype studies using these approaches suggest that significant increases in energy efficiency, speed, and multimodality are possible. Relative to design features such as swashplates, reduced complexity and manufacturing costs are possible.

Critical Thinking and Innovation – The lifting body VTOL is a result of critical thinking based on the three Principles, and the three principles identify that a surface, or intersecting velocity vector, is needed to transform velocity into pressure. To a first approximation, the downward velocity of a lifting propulsor (i.e., ducted fan, tiltrotor, tiltwing, rotary wing) is lost work. The use a lower cavity and horizontal flow created from the downward flow through a duct to transform velocity into pressure allows for a reduction in the total lost work. The transformative process is identified by the first principle, which is an example of how the principles teach toward improved vehicle and device designs in engineering.

The reversibility of velocity-pressure and pressure-velocity transformations can be very high. Both transformations regularly occur at elbows in pipes, for propeller blades, for centrifugal pumps, and for numerous other devices. The generation of pressure followed by subsequent generation of velocity commonly achieve efficiencies in excess of 90% in these common devices.

New Benchmarks of Performance – New benchmarks of performance emerge in the equations and conclusions of this paper. One benchmark is that lost work goes to zero in the ideal limit of ground effect lift when the area through which flow expands outwards as lost work goes to zero. A second benchmark is that the work necessary for steady-level flight approaches zero as translation increases since no work is performed in the vertical direction; however, viscous drag will always be present.

A new approach to vehicle design is through pressure contour engineering where propulsors gain the important purpose of redirecting flow to prevent boundary-layer separation, augment lift beyond what is seen through surface structure, and control sources of lost work. In this approach, under the assumption that propulsors can create pressure and flow and efficiencies in excess of 90%, considerable advances can be made towards efficiencies in generating aerodynamic lift, resulting in much-higher lift-drag ratios.

The approach of pressure contour engineering tends to contradict distributed propulsion techniques that increase frontal-projected areas (“frontal areas”) of aircraft. For example, banks of propellers above a wing ultimately increase drag and the frontal-projected area. Alternatively, ducts and propulsors within the otherwise functional frontal-projected area has greater perspective for increased efficiency.

The pressure contour engineering approach includes ground effect flight applications. Ground effect flight may be augmented with wheel or ski suspension to enable valuable degrees of freedom for multimodal transit on current and future highway/railway/waterway corridors. Specifically, pressure contour engineering with propulsors can be used to decrease the drag of automobiles and trucks which may or may not utilize aerodynamic suspension. The current work of lifting body vertical lift expands multimodal transit to highway/railway/waterway/airway multimodality by using lifting-body vertical lift to efficiently transition to free flight, improving interconnectivity.

The aerodynamic approach has utility for a wide range of fluid dynamic applications and increasingly useful interpretations of: a) lifting body flight, b) streamlining all vehicles, c) centrifugal pumps, d) design of advances in marine/naval vessels, and e) hydrodynamics.

An Extended Perspective

An Extended Perspective – The evolution toward the lifting-body vertical takeoff approach of this paper originated as a project to create a more-efficient and faster air taxi. A change in R&D methods from concept-based remote-control scaled prototypes to CFD digital prototypes created many levels of innovation; most importantly, the use of Navier-Stokes-based CFD simulations provided improved understanding.

A previously published perspective by the authors identifies the advantages of ground effect technology on railways to enable higher speeds and efficiencies on existing highway/railway/waterway infrastructure [12]. This work provides an improved understanding of how to achieve increased efficiencies with ground effect flight.

A problem with ground effect vehicle designs is the rapid loss of lift as the clearance between lower-surface perimeter fences increases. The novel dynamics of the vertical impeller of this work provides a more-robust and efficient lift which will not diminish as quickly with increasing ground clearances. For ships, more-robust and efficient lift at higher clearances enables transit over rougher waters, making ground-effect flight ships viable during most all sea conditions. Vertical takeoff enables takeoff and landing in rough seas as well as transformation to lifting body flight that is potentially more efficient than other aircraft.

The ability to selectively create lift on the vast majority of planform areas creates a new approach to aircraft design. The classic cylindrical fuselage with wing design tends to emphasize use of high-lift wings and low-drag cylinders with efficiency increases from incremental perturbations. Flying wing designs emphasize air flow around the lifting body airfoil to generate lift. The ability to create lift at strategic planform locations with ducts and propulsors can tweak the aerodynamics to maximize lift and efficiency. To a first approximation, the anterior recovery and aft recovery dynamics of Figure 3 should apply to pressures created by ducts and propulsors which creates valuable design degrees of freedom.