Critical Data and Thinking in Ground Effect Vehicle Design

Introduction

A new ground effect transit vehicle (GEFT) evolved in design over an eight-month period and has digital prototype lift-drag ratio (L/D) efficiencies double those of past ground effect vehicles (GEV). The evolution of the GEFT design is attributed to an improved simple explanation of how air flow is converted to aerodynamic lift.

The design may be especially high-impact because critical aspects of the design have synergies with low-aspect ratio vehicles, making the resulting vehicles compatible with transit on railway, highway, and waterway corridors as well as free flight. This compatibility transitions aircraft, railway, watercraft, and automobile sectors including solar-powered vehicles and a new version of a flying taxi.

Seminal works document both the designs and thought processes behind traditional designs with changes in designs directly linked changes in explanations of how air flow generates aerodynamic lift. Computational fluid dynamics (CFD) and the molecular theory of gases provide insight into the science including causality and extrapolation of designs.

Background

Patent claims of the GEFT design date to December of 2023 when a low aspect ratio aircraft using "Lift Span Tech" was computationally evaluated in flight over railway tracks to use the tracks to block spanwise loss of lift pressures under the vehicle. Two findings of the analysis were: 1) the combination of tracks on the ground with fences on the vehicle were effective in blocking lateral losses of lower-surface lift pressures and 2) the ground blocked vertical loss of lift pressures which appeared to have a greater positive impact on L/D efficiency than blocking the spanwise loss of lift pressures.

Initial emphases of the first year, 2023, of computational fluid dynamics (CFD) studies on this project were on better understanding how air flow creates aerodynamic lift. Of particular interest was the poor L/D efficiency of a flat plat airfoil at a pitch of 1° when the geometry suggested that the ratio of vertical to horizontal forces should be 57 with a resulting L/D efficiency of 57 with minor corrections for viscosity drag. To achieve this objective and possible use of distributed propulsion to improve the L/D efficiency, the following computational studies were performed:

1. Performance of flat plate and thin-cambered airfoils,
2. Impact of propulsor source location on L/D efficiency of thin-cambered airfoils, and
3. Impact of wing section thickness on propulsor source location to increase L/D efficiency.

These studies in combination with the 2024 studies on ground-effect flight resulted in identifying the following principles of physics as identifying causality for how air flow creates aerodynamic lift and higher L/D efficiencies:

Principle 1. Impacting air flows create higher surface pressures.

Principle 2. Diverging air flows create lower surface pressures.

Principle 3. Air flowing from higher to lower pressures at the speed of sound extends lift pressures along streamlines, dissipates lift pressures across streamlines, and interacts with air flow to turn streamlines.

Principle 4. The L/D of a section of an airplane surface is approximately equal to 57° divided by the pitch of the surface in degrees for lower surfaces and -57° divided by the pitch for upper surfaces. The pitch angle is relative to horizontal with the nose up as positive.

Principle 5. Surfaces can be used to block loss of lift pressures leading to increased L/D. Example surfaces are winglets on wing tips and fences under lifting bodies.

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Principle 6. For a ground-effect aircraft with a properly-designed lower fenced cavity, 3D CFD estimates of cavity lift pressures are able to approach 2D estimates, enabling 2D airfoil simulations to accurately predict actual performances and trends in many applications.

The following guideline supplements these principles:

Heuristic 7. For NACA-type airfoils, L/D efficiency increases with a decreasing [clearance]:[chord] ratio; for airfoils using distributed propulsion to truncate chord length while counteracting boundary layer separation formation, the L/D efficiency increases with decreasing ratios of [clearance]:[height] ratios; these trends tend to apply to [clearance]:[height] ratios between 0.04 and 2.

Wing in Ground Effect versus Lifting Body – Ground effect vehicles which use oncoming air to generate aerodynamic lift fall into the category of either wing-in-ground (WIG) or lifting body design. WIG aircraft generate lift primarily from laterally extending wings, are not limited to ground-effect flight, and are the emphasis of current commercial efforts such as the Liberty Lifter, Airfish 8, and Regent aircraft [1-6].

Ground effect machines (GEM) are a category of ground effect vehicles that includes both hovercraft and lifting-body designs. Figure 1 compares the Smith and GEFT GEM designs [7]. In this paper, GEM refers to designs that can exhibit aerodynamic from both hovering thrust and aerodynamic suspension due to air's oncoming flow interacting with the GEM's lifting body.

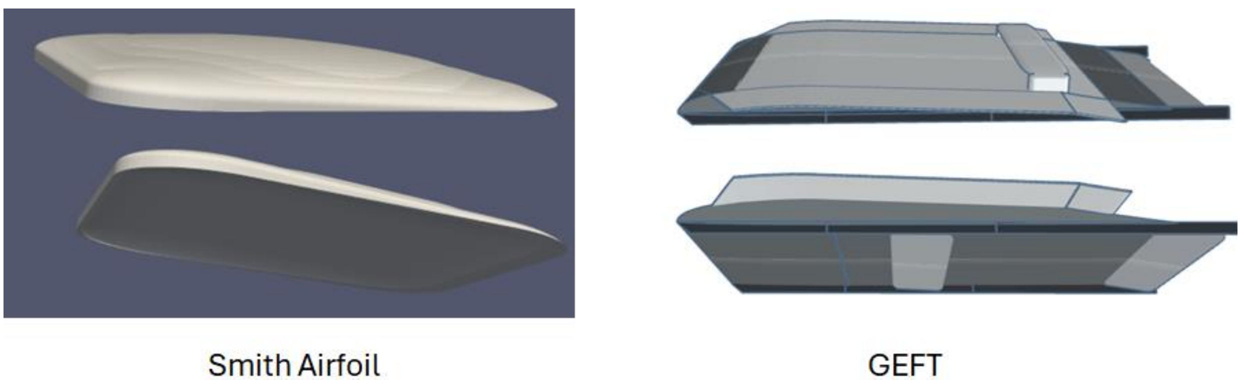

Figure 1. Comparison of GB1347352 (Smith Design) to GEFT ground effect machine (GEM). The preferred propulsion for the Smith Airfoil is a crossover propulsor (not shown) while the preferred propulsion for GEFT is an upper-surface trailing-section propulsor in a Lift Span Tech configuration.

Strategic objectives of ground-effect aircraft are to carry heavier payloads with shorter wingspans and to fly at greater L/D efficiency. Both aerodynamic lift and L/D efficiency increase in ground effect as the aircraft approaches the ground. Past works correlate the increases in L/D efficiency with decreases in [clearance]:[chord] ratios. Work on GEFT with distributed propulsion correlates L/D efficiency with the ratio of [clearance]:[height] where the height is the forward-projected profile of a lifting body at zero vehicle pitch.

The tolerance of bumps on roads and open terrain, as well as waves on water, dictate a minimum clearance for flight without contacting the ground. Correlations between that clearance and the lift of the aircraft are a key metric for GEM. For example, a fuselage that is 4X as thick as a wing is able to fly at higher efficiency at the same ground clearance.

GB134752 and GEFT use fences to further remove the lifting body from the water surface while sustaining higher efficiencies. WIG designs use downward projecting winglets to achieve a similar, but less effective, conservation of lower-surface lift pressures. Because lift pressures dissipate at the speed of sound, winglets of shorter chord are less effective than fences when

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used in conjunction with the ground to prevent dissipation of lift forces. The ground-effect vehicles tend to have planforms similar to a barge's planform where lateral wings are optional and primarily advantageous for higher efficiency in free flight.

Figure 2 compares the centerline wing sections of the Smith Airfoil to GEFT. The Smith airfoil has a concave lower surface while GEFT has a flat lower surface followed by a flap. Features A-C dominate GEFT's upper surface as follows:

- **A.** A near-horizontal surface immediately forward the intake of an upper-surface trailing-section propulsor,
- **B.** A steep trailing taper at the discharge of the propulsors.
- **C.** A truncated length.

The combination of GEFT's section "A" and "B" with a propulsor transition is referred to as "Lift Span Tech", which in its optimal configuration, includes morphing surfaces that maximize L/D efficiency with the pressure forces of the propulsor.

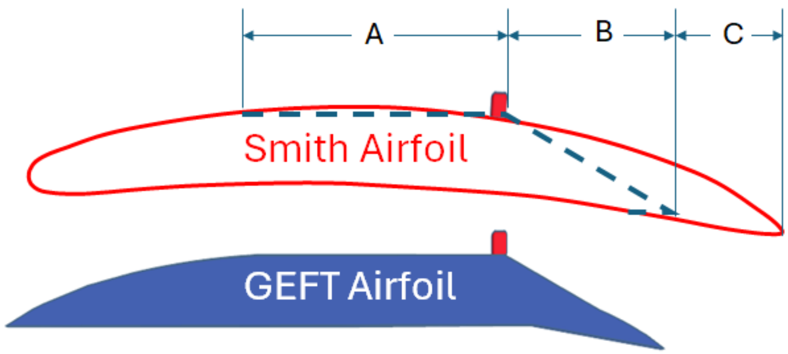

Figure 2. Comparison of GB1347352 to GEFT centerline wing sections with indication of GEFT propulsor.

At low clearances, the lift pressures of GEFT's lower cavity approach oncoming air's dynamic pressure where lower-surface lift pressures are relative to free-stream pressure and air's dynamic pressure is $0.5\ \rho\ u^2$ (***u*** is velocity, ***ρ*** is air density). This higher lift pressures are expresses on the entirety of the lower surface with two advantages emerging for lifting-body designs:

- Lower aspect ratios which allow the vehicles to travel in narrower corridors like roadways and railway corridors and
- Increased aerodynamic lift.

In addition, GEFT claims L/D efficiencies twice those of WIG counterparts. Claims of GB134752 are limited to the translational L/D efficiency of the GB134752 design being considerably greater than the L/D efficiency at lower-velocity hovercraft modes of operation.

Performance Trends – Two performance trends have dominated prominent schools of thought on ground effect vehicles. First, the L/D efficiency has been correlated with the [ground clearance]:[chord length] ratio [8-14]. Second, Induced drag is associated with limiting the upper L/D efficiency [15, 16].

This paper critically evaluates the thought processes identified in GB134752 to the path of innovation of GEFT. Digital prototypes are compared to quantify the differences, and discussions are continued based on other schools of thought on lifting body ground-effect vehicle designs.

Lost Work Analysis – A lost work analysis provides insight into how ground effect and Lift Span Tech increase L/D efficiency. The Figure 3 control volume is evaluated at steady-state. In ground-effect, the lower surface is the ground with streamlines parallel to the ground and the ground blocking dissipation of lift pressures downward. The primary manifestation of lost work in aerodynamics is: a) velocity vectors of air exiting the aft control surface at magnitudes and directions differing from the free stream velocity vectors entering the forward control volume surface, b) waste heat in the form of higher-temperature air exiting the aft control volume surface, and c) pressure force dissipating vertically through the upper control volume surface characterized by pressure gradients (i.e., variance of blue color intensity).

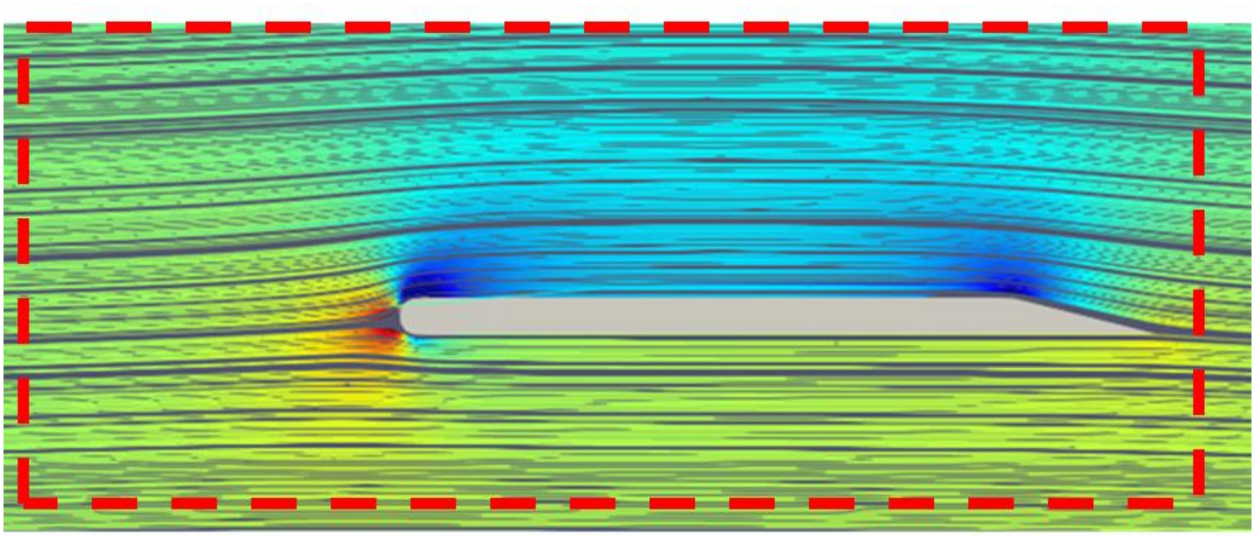

Figure 3. Control volume as red dashed line for system's level analysis of an airfoil.

Drag Definition – The many definitions of drag in aerospace literature overlap and are often poorly defined. For purposes of this work, the following definitions of drag will be used and only applied in steady-level flight:

- **Pressure Drag** – The horizontal component of force due to pressure acting on a surface.
- **Viscous Drag** – The horizontal component of force due to shear stress of a fluid along a surface.
- **Total Drag** – The sum of pressure drag and viscous drag.
- **Induced Drag** – Pressure drag on a surface section with vector orientation horizontally rearward.
- **Induced Thrust** – Pressure drag on a surface section with vector orientation horizontally forward.

The CFD simulations of this work provide pressure and viscous drag as outputs. The term "Induced Thrust" is used because of its importance in optimizing L/D efficiency and its functional distinction from induced drag.

Methods

OpenFOAM CFD software was used to simulate digital prototypes prepared as STL files. Two-dimensional (2D) simulations were used to identify trends in performance while 3D simulations were performed on the final prototypes. Unless otherwise reported, the scale chords of the STLs were 1 m, the fluid was air at 1 atm pressure, and the free stream velocity was 40 m/s. Pressure profiles are presented with blue as low pressures, red as high pressures, and a symmetric scale where 0 gauge pressure is green. Computer aided design (CAD) was used to create STL files for the Smith Airfoil and GEFT by combining common geometries.

For ground effect simulations, the ground was simulated as a lower boundary condition with a velocity equal to the free stream air.   Unless otherwise identified, the propulsion sources were rectangular with a height of 2 cm and thickness of 2 mm. Free steam flow boundaries were simulated at a minimum of 5 chord lengths from the vehicle in free stream directions.

Both 2D and 3D CFD simulations were performed. 2D simulations are referred to as being performed on airfoils or wing sections. 3D simulations are referred to as being performed on digital prototypes or GEM.

Results

Details presented in GB1347352 allow the Simith airfoil and cavity design to be compared to corresponding features of GEFT as summarized in Table 1. Most differences provide sufficient details for the Discussion; however, additional information is needed to understand the Smith GEM specifically identifies the need for additional energy to overcome "profile drag" while the issue is less prominent with GEFT.

Table 1. Critical performance feature comparison of GB1347352 to GEFT [7].

FEATURE	GB1347352	GEFT
Fences	For Hovering: "flaps, skegs, or fences" (p3,l9)	Side fences, a trailing-edge flap, and optional slats. Vertical movement of fences is used to control pitch and roll.
Efficiency	Efficiency increases with translation	Efficiency increases with translation.
Source of Lift	Continuation of cambered mean line 22 (p2,l75, Fig 4)	A flat lower surface with trailing flap is preferred in combination with fences of equal clearance from the ground when not adjusted in control.
Dissipative energy	"no corresponding dissipative energy as in conventional reduced drag" (p3,l45)	
DRAG		
Profile Drag	Profile Drag – "in translation additional energy is needed to overcome profile drag" (p3,l50)	
Flat Lower Surface	Identifies concave cavity as important for air flow velocity to convert to pressure due to reduced velocity as the cross-section increases	Identifies the Principle 3 extension of pressure rearward from the leading-edge stagnation point and forward from the trailing-edge stagnation point which effectively occurs when fences and the ground block downward and lateral pressure dissipation.
THEORY		
	Velocity is proportional to area (p3,l120)	Velocity impact higher pressure in cavity and decreases due to the same mass flowing at a higher density.
	Bernoulli Relationship (p4,l1)	The inter-conversion of pressure and velocity is important, but extension of pressure is of equal or greater importance.
	Energy is required to provide the sealing curtain (p3,l48)	A surface may be used to block lift pressure dissipation, lost lift pressure must be replaced by air's dynamic pressure

CFD Simulations – A thin cambered airfoil can achieve high L/D efficiency in ground effect as a wing section. Figure 4 compares the performance of several wing sections.

Induced drag consistently forms on the trailing section upper and lower surfaces via lower pressures on the upper surface section and higher pressures on the lower surface section. The trailing section induced drag can be neutralized by induced thrust forming on both upper and lower surfaces of the forward section.

In 2D simulations, pressure forces below the lower surface dissipate downward, then forward or backward. When the higher pressure extends aft or fore the wing section, pressure forces may dissipate upward. As the clearance decreases, the dissipating flux occurs through a smaller area between the wing section and the ground which reduces the total dissipation; resulting in more induced thrust and higher L/D efficiency.

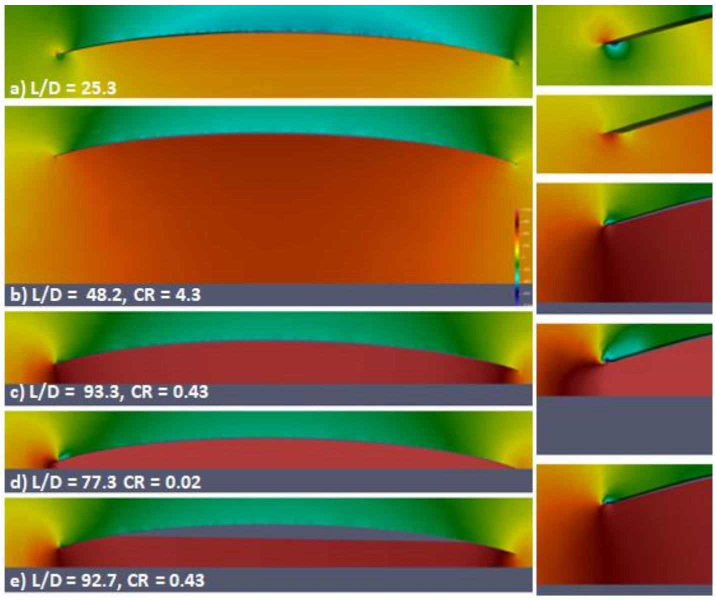

Figure 4. Pressure profiles of study on simple 0.06 camber airfoil at 1° pitch of thin cambered wing sections (i.e. 2D CFD).

In 3D, spanwise loss of lift pressures add to the vertical and chord-wise losses, exasperating the dissipation of lower surface lift pressures and loss of induced thrust. More-detailed studies of approaches to GEFT design identified that filling the lower cavity toward a horizontal lower surface eliminates the lower surface induced drag and is the preferred approach to increase L/D efficiency per Figures 1 and 2 [17].

Pressure profiles of the Smith airfoil are summarized at increasing vehicle pitch angles (Figure 5) and increasing source power (Figure 6). The clearance with the ground was also varied (Table 2). The L/D efficiency peaked at about 17 (Table 2) which is considerably less than typically >30 for the GEFT airfoil with optimal conditions leading to L/D > 40. A number of factors lead to the lower L/D of the Smith airfoil, including:

- **Loss of Cavity Lift Pressure -** When pitch angles increase, the clearance at the front of the vehicle increases leading to spanwise loss of lift pressures with induced drag on the lower surface of the leading section.
- **Induced Drag -** With surface pitch angles >4° on the upper-surface trailing section, the formation of lower pressures leads to induced drag with surface contributions of L/D of <57/4. A trailing-section upper-surface propulsor exasperates this phenomenon.

These trends were exhibited in studies of thin cambered airfoils of Figure 4 and as a subject of more-extensive studies [18].

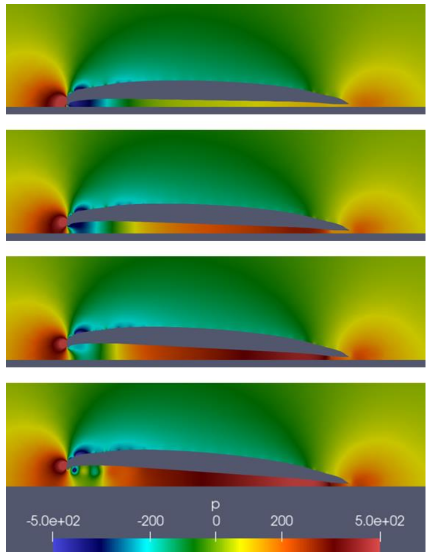

Figure 5. Pressure profiles of Smith GEM digital prototype (3D) pitch angles of 0, 1, 2 and 3 at a 0.118 clearance ratio (1cm clearance). Pressure in m^2/s^2.

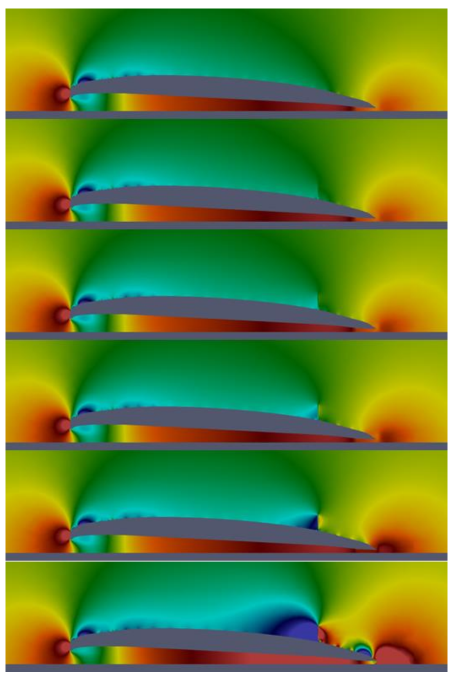

Figure 6. Pressure profiles of Smith GEM digital prototype (3D) with upper-surface trailing-section propulsor.

As indicated by Figure 7 and Table 2, the Smith airfoil (at an aspect ratio of 0.7), is designed to operate most effectively at a low angle of attack, between 1 and 3 degrees, with about a 1:15 ratio of clearance to height. Without adjustable fences to maintain clearance throughout the cavity perimeter, increased GEM pitch leads to low L/D efficiency than otherwise possible due to additional loss of lift pressures from the forward sections of the cavity.

The optimal performance is over a narrow range of GEM pitch angles. For GEFT operating at optimal fence and flap settings, the preferred methods to increase vehicle height are with increased velocities or increased pitch. The use of increased pitch angles provides quicker response to achieve free flight.

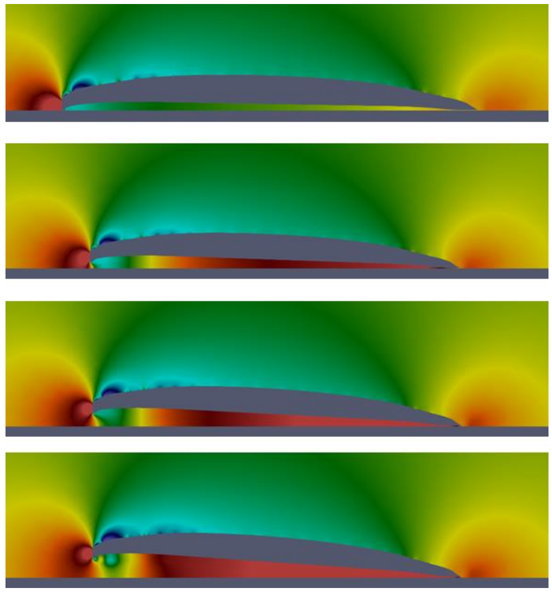

Figure 7. Pressure profiles of Smith GEM digital prototype (3D) pitch angles of 0, 1, 2 and 3 at a 0.02 clearance ratio.

Table 2. Summary of Smith GEM (3D) performance. The source location is as indicated by Figure 2.

Clearance Ratio	GEM Pitch	Source Setting	Cl	Cd	L/D
0.02	0	0	0.69	0.053	13.0
0.02	1	0	2.19	0.127	17.2
0.02	2	0	2.70	0.181	14.9
0.02	3	0	2.99	0.233	12.8
1.18	0	0	0.67	0.094	7.2
1.18	1	0	1.35	0.121	11.2
1.18	2	0	1.87	0.154	12.1
1.18	3	0	2.26	0.198	11.4
1.18	2	1	1.87	0.154	12.1
1.18	2	2.5	1.90	0.157	12.1
1.18	2	5	1.93	0.157	12.3
1.18	2	10	1.99	0.160	12.4
1.18	2	50	2.81	0.247	11.4

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Impact of Smith Crossover Propulsor – GB1347352 includes cross-over propulsors with propulsor intake at an upper surface of about 6° pitch and discharge into the lower surface cavity. The crossover propulsor increases but has minimal impact on reducing induced drag from the lower upper-surface pressures on the aft half.

Crossover propulsors are able to "top off" the dynamic pressure of oncoming air and create more lift at lower pressures. At lower velocities, the Smith machine operates as a hovercraft, while at higher velocities the oncoming air creates enough lift to support vehicle weight. Increasing power of the crossover propulsor had minimal impact on L/D efficiency.

GEFT, Fences, and Horizontal Lower Surface – Fences can reduce spanwise loss of lift pressures. Use of fences as control surfaces enables the fence clearance to be constant while the pitch of the vehicle changes which is able to transform the lower-surface leading-section induced drag into an induced thrust.

Figure 8 provides centerline pressure profiles of a GEFT digital prototype benefiting from Lift Span Tech, side fences at constant clearance, and a filled camber having a horizontal lower surface.

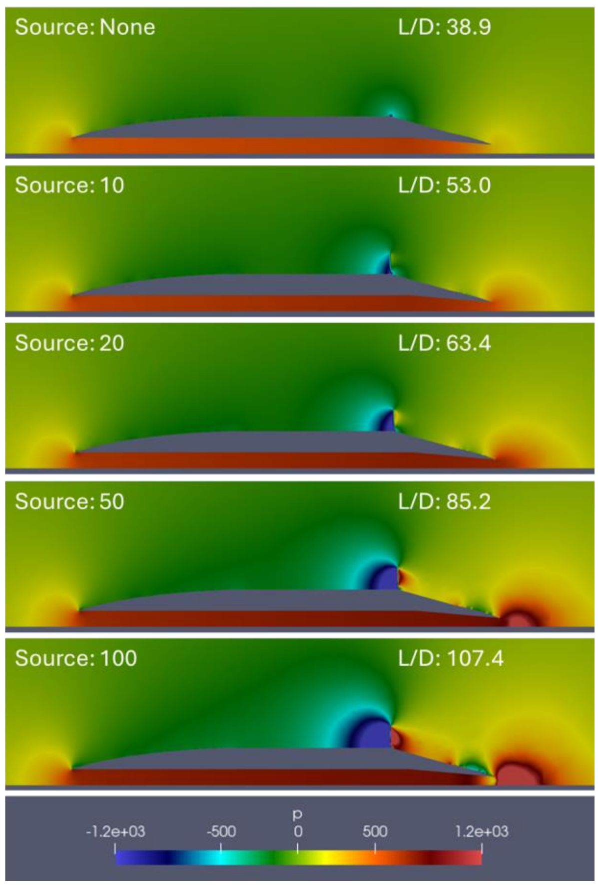

Figure 8. The impact of sources on a 3D GEFT with 1m length at fence clearance ratio of 0.04 [19].

The Lift Span propulsor of the Figure 8 GEFT design adds the following fundamental performance characteristics [20]:

- Lower intake pressures expand to the front of the vehicle creating induced thrust and increased lift,
- Induced drag of the trailing taper is reduced by increasing respective surface pressure.

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- A trailing edge stagnation point intensifies as increased velocities increase the pressures generated from the collision of two air streams of different velocity vectors at the trailing edge, leading to expansion of higher pressures forward into the lower surface cavity.

No attempt was made to match propulsor thrust with vehicle drag. Accordingly, L/D efficiencies in excess of 80 do not correspond to steady-state operation. In general, L/D efficiencies greater than 50 have increasing error due to the high impact that small increases in drag can have on L/D efficiency. Useful insight can be gained from these trends as discussed infra.

Discussion

Induced Drag – The lower pressures on the upper-surface area of the trailing half of all Smith airfoils create induced drag. While the crossover propulsor increased lift, it has minimal impact on the induced drag of the upper-surface trailing section. An upper-surface propulsor at a location similar to that of GEFT's propulsor created additional induced drag.

The induced drag increases as the pitch of the trailing-section upper-surface increases. Hence, for the Smith airfoil, L/D efficiency correlates with [height]:[chord] ratios. This constraint limits the practical application of the Smith machine toward use with thicker airfoils for passenger compartments and larger payloads. Extended chord lengths to achieve larger scales also increase costs.

The GEFT airfoil uses Lift Span Tech to truncate the chord length a high-pitch surface aft an upper-surface trailing-section propulsor. A design criterion is to balance the pitch of the trailing taper with the higher-pressure discharge of the propulsor to achieve a near-ambient-pressure-averaged surface pressure on the taper for near-zero induced drag. This same criterion correlates with minimizing the expression of lost work in the streamlines aft the airfoil as detailed in the subsequent discussion of lost work.

Induced thrust is critical to modern aircraft performance; induced thrust allows the pitch of a wing to increase with minimal change in L/D over several degrees of change. For the lost work analysis of the following paragraphs, thrust is provided in the first region in the form of induced thrust on the forward section of the lifting body.

Figures 9 and 10 summarize performance trends for GEFT. At optimal low-clearance performance, GEFT's lower cavity's pressure prototype simulation approaches the 2D cavity pressures from the leading-edge stagnation point to a trailing-edge stagnation point. This is illustrated by Figure 8 pressure profiles. The maximum increase in lower cavity pressure is the dynamic pressure of oncoming air relative to the GEM.

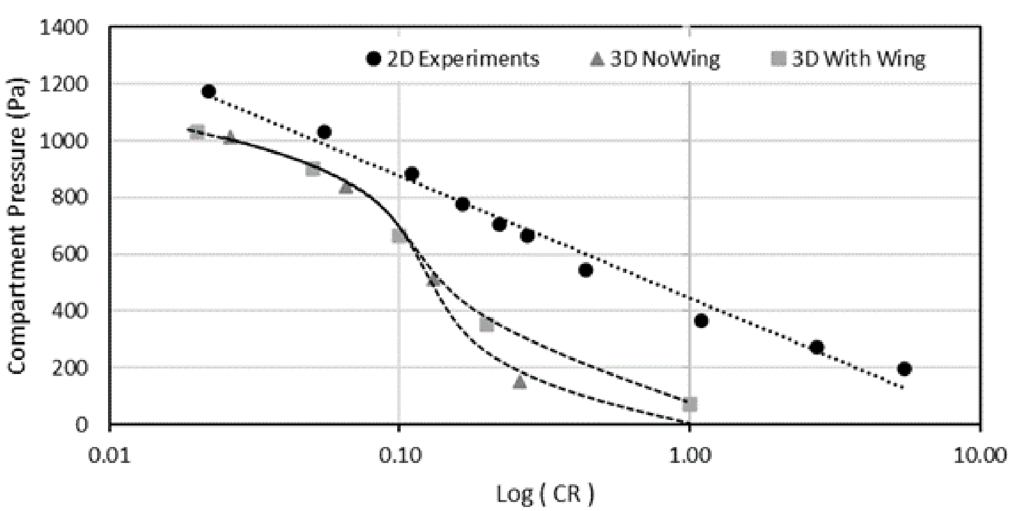

Figure 9. Impact of clearance ratio on average cavity pressure.

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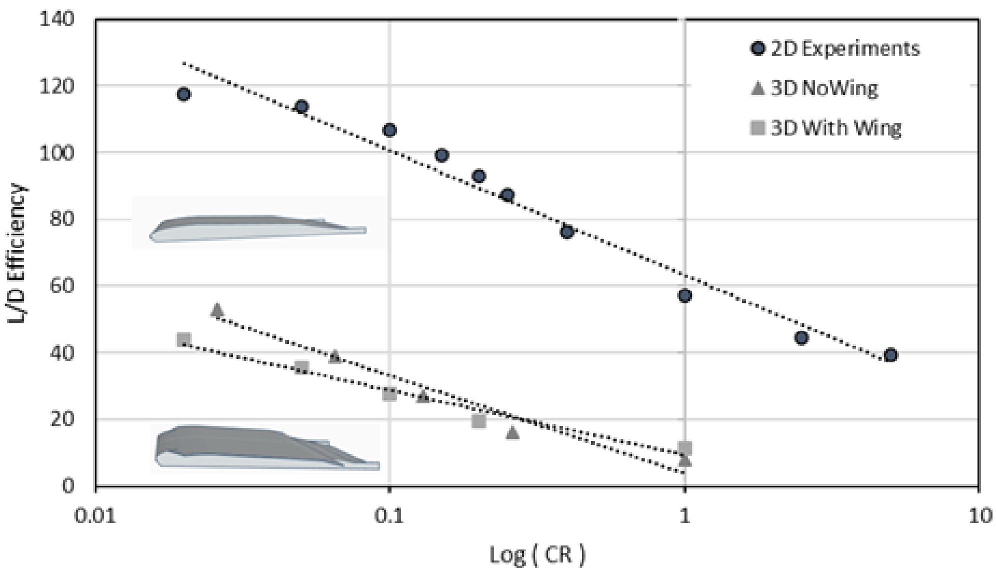

Figure 10. Impact of clearance ratio on L/D Efficiency.

GEFT's L/D efficiency tends to increase with increasing cavity pressure. The impact of lateral wings depends on the wing design and is primarily advantageous in free flight.

Lost Work Analysis - For an airframe with a horizontal upper surface and a sudden trailing taper, boundary layer separation occurs along with a range of velocity vectors. When Lift Span Tech distributed propulsion is added to the wing section, the propulsor disrupts the velocity vectors in the transition to the trailing taper.

When the discharge includes higher pressures, the higher pressures will expand along the taper surface and potentially eliminate boundary layer separation. A given thrust force of a propulsor discharge can operate over a range of pressures and velocity vectors. The efficacy of eliminating boundary layer separation depends on the propulsor power, discharge pressure over the taper, and discharge velocity vector distribution.

On a more-comprehensive basis, degrees of freedom impacting the flow at the trailing control volume surface of Figure 3 include: i) magnitude of propulsor power, ii) discharge air vector profile of the propulsor as impacted by several factors including blade shape and duct surface shape, iii) the shape of the trailing taper, iv) other features such as spoilers, and v) the proximity to the ground and shape of the cavity exit. Within these degrees of freedom, it is possible to create a relatively constant discharge with parallel velocity profile to the leading surface of the control volume; this condition corresponds to a minimum in lost work exiting the trailing control volume surface of Figure 3.

Figure 11 and Table 3 illustrate the transition that can occur for a lifting body with Lift Span Tech. At zero propulsor velocity boundary layer separation occurs at the onset of the trailing taper as characterized by a modest L/D of 20 and an area of turbulence above the trailing taper. At a propulsor setting of U=2.5 m^4/s^2, the velocity profiles behind and above the trailing edge are uniform indicating minimal lost work with an L/D = 42. As the power of the propulsor is increased further, a jetwash stream forms (white on velocity profile) immediately above the trailing taper and continues behind the vehicle.

As the propulsor power increases above 2.5 m^4/s^2, L/D efficiency appears to increase; however, the incremental [gain]:[loss] ratio of gain in L/D versus loss in propulsor power is poor with increasing lost work. From a propulsor power of 0-2.5 m^4/s^2, the increased propulsor produces both thrust and reduces lost work, it is a win-win scenario as part of optimizing

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operation. The minimum in lost work exiting the trailing control volume surface correspond to the onset of the trailing-edge stagnation point.

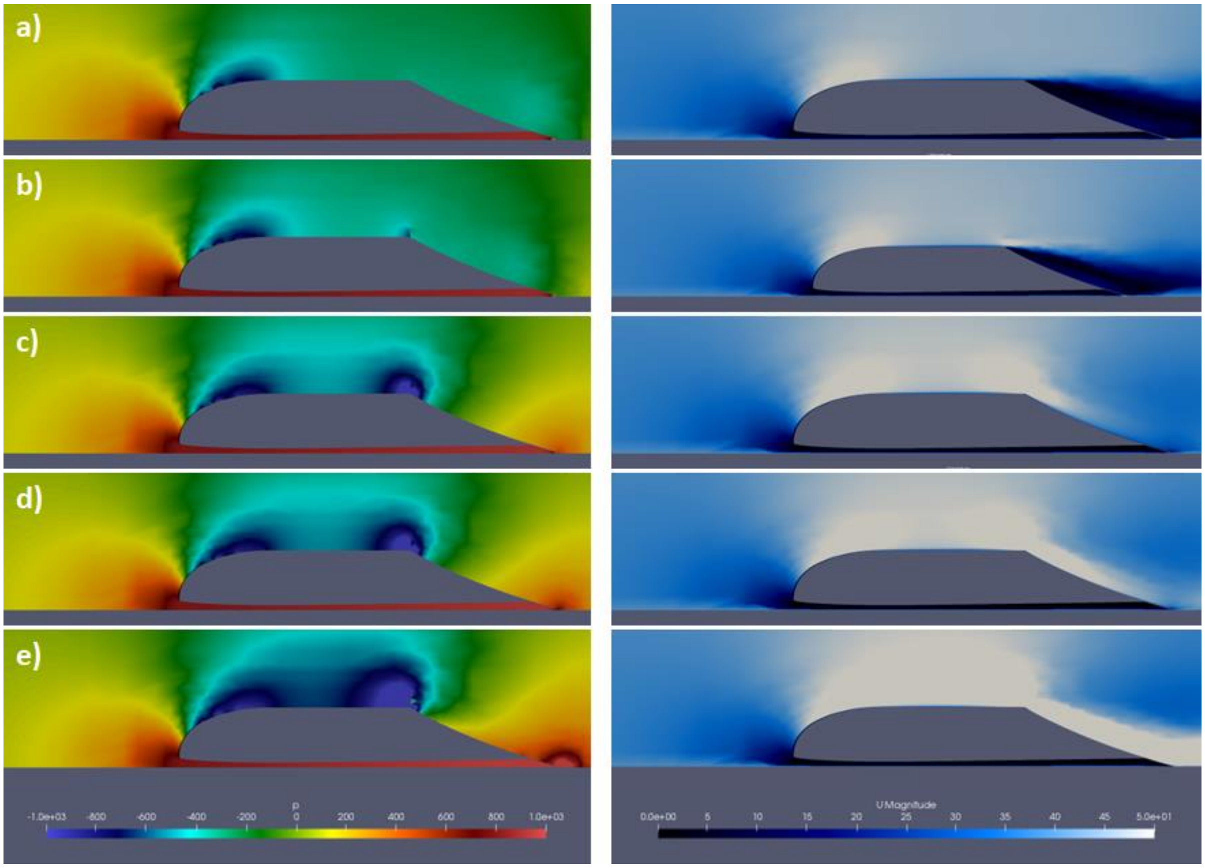

Figure 11. Pressure and velocity profiles of high thickness ratio GEFT wing sections. Pressure (P) is in m^2/s^2 and velocity (U) is in m/s.

Table 3. L/D ratios and propulsor settings for Figure 11 wing section profiles. Simulations are at 40 m/s and 1 atm free stream conditions. *533 L/D is the result of a disproportionately small coefficient of drag where propulsor thrust manifests as surface pressures on the wing section.

	S (m^4/s^2)	U (m/s)	L/D
a)	0	40	20
b)	1	40	21
c)	2.5	40	42
d)	5	40	53
e)	20	40	533*

The jet wash phenomena at propulsor settings above 2.5 m^4/s^2 are flows of increased velocity reflective of the increased momentum in the air which provides additional thrust. Propeller, fan, and jet efficiencies have characteristic curves of performance where increased momentum of air in the discharge increases thrust with reducing efficiency.

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Figure 12 summarizes overall trends of an optimally applied Lift Span Tech propulsor. The initial propulsor power eliminates the boundary layer separation with gains in overall efficiency exceeding the additional power provided to the propulsor. At higher propulsor settings, increasing magnitudes of jet wash decrease overall efficiency after the overall maximum system efficiency is reached.

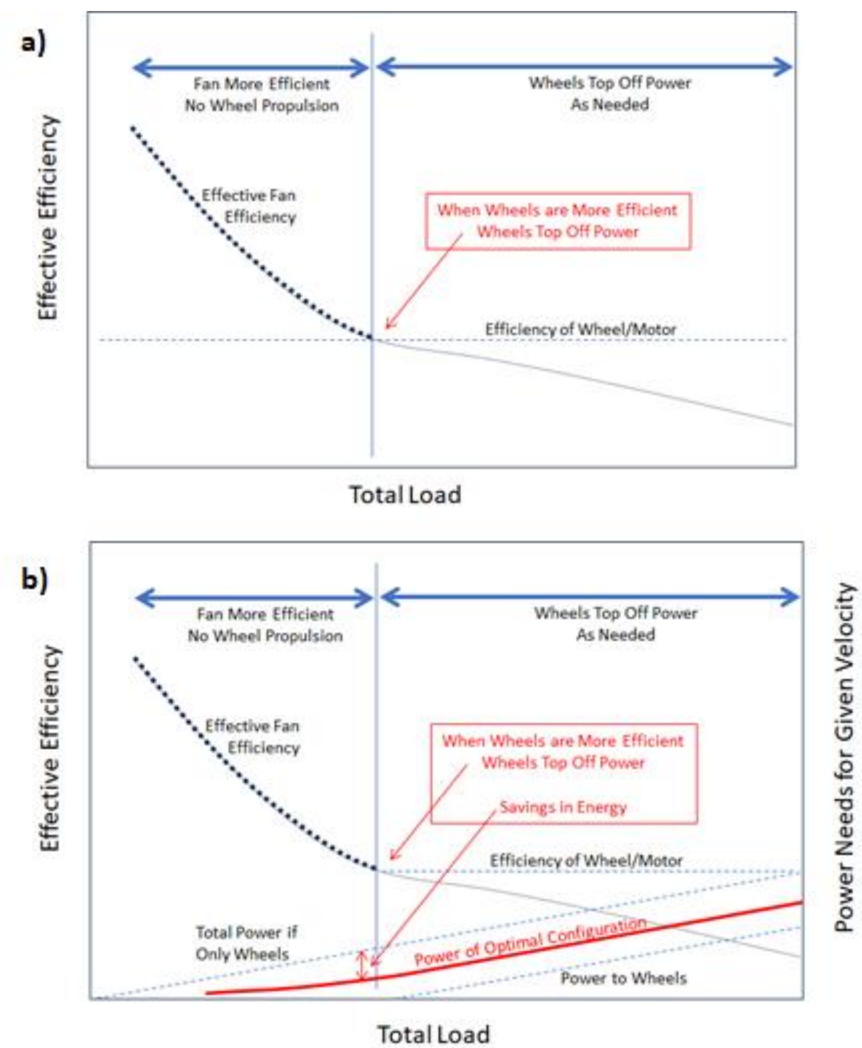

Figure 12. Illustration of optimal operation for propulsor that reduces drag as power increases: a) at lower total loads the fan is more efficient than wheels and b) when wheel propulsion tops off fan propulsion at higher loads a savings in energy is achieved.

Figure 12 considers a vehicle capable of both wheeled propulsion and Lift Span Tech propulsion. Figure 12a illustrates how the effective propulsion of a fan is greater than wheel efficiency at lower loads since the fan both provides propulsion and reduces drag. Optimal operation would have the wheels supplement efficiency for loads above thresholds where the wheels become more efficient. Figure 12b illustrates the impact on total power and savings in overall energy costs. The performance is design-dependent and dependent on the velocity of translation.

When operating at a load where fan-based propulsion is sufficient (i.e., left side of diagram), ground effect without wheel supplement of suspension is preferred, unless wheels are used to

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keep the fences close to the rails or roadway. If wheels are used to keep the fences close to the ground, a nominal load should be placed on the wheels to assist in maintaining tight clearances.

The implications of the trends are most significant because they indicate that a gamut of trucks, busses, and automobiles would benefit from Lift Span Tech—often reducing power requirements by nearly 50%. The implications also identify that Lift Span Tech bridges the gap between aerial transit and highway transit. The January 2024 TRB paper identified that GEFT technology as a bridging technology between air and some types of land transit [20]. This work provides details on how Lift Span Tech bridges the gap between the most prominent and fuel-intensive highway transit and air transit.

A control algorithm emerges where for some applications of a Lift Span propulsor and trailing taper they are optimized to minimize drag with minimal lost work in the form of jet wash. In this application, other propulsion sources such as wheels provide the thrust requirements.

A rigor in second law analysis, i.e. lost work analysis, would include calculations of the available energy of all streams entering and exiting the Figure 3 control volume. The more-practical value of such analysis would compare different propulsor locations and combinations of multiple propulsors. The computational power of such an analysis is beyond the capabilities of this project. In lieu of quantitative rigor, Table 4 summarizes identified types of lost work at the four surfaces of Figure 3 toward more-definitive conclusions on GEFT's profile drag and areas for further improvement.

Table 4. Summary of Lost work analysis on GEFT other than viscous drag.

Optimal Lower Surface	LOW LOST WORK – Since streamlines do not traverse the ground, typical forms of lost work associated with streamlines are eliminated. With assumptions of negligible heat transfer and ground movement, the lost work on the lower control volume is essentially zero.
Spanwise cavity losses	LOW LOST WORK – The same arguments for the ground apply to side fences toward near-zero lost work. As the fence clearance decreases, lost work decreases until such clearance that viscous drag between the lower fence edges and ground become substantial; this has been attributed to decreases in L/D as the [clearance]:[height] ratio becomes less than 0.02.
Optimal Lift Span Trailing Taper	LOW LOST WORK – An optimal trailing taper has an average surface pressure near free-stream pressure and a uniform velocity profile. The result is low lost work through the aft surface except heat from viscous or turbulent losses within the control volume.
Lift Span	A -1° to 0° degree surface pitch for most of the mid-chord upper surface produces no form drag. The primary lost work is vertical dissipation of lift pressures (lower pressures) with lateral losses from the vertical stratification. Morphing surfaces can minimize form drag as a function of propulsor power. When operating in ground effect, upper surface lift pressures are not necessary where the absence of upper surface lift pressures can substantially eliminate lost work through the upper control volume surface.
Upper Frontal Section	An optimized curvature of the frontal section produces a continuous development of divergent flow that leads to lift and induced thrust. A leading-edge stagnation point is necessary to create the divergent flow that leads to the continuous creation of induced thrust. An even development of divergent flow tends to minimize lost work from upward pressure dissipation

Further Distributed Propulsion and lateral wings	Upward dissipation and spanwise dissipation of lift pressure is the primary lost work of an optimized GEFT, two approaches reduce these losses: a) further distributed propulsion for multiple locations of modest lower pressure rather than a single location of higher magnitude lower pressure and b) laterally-extending wings or fences to moderate spanwise losses. Optimal configurations depend on operational clearances and extent of free flight during normal operation.

The Table 4 summary identifies how the ground and fences substantially eliminate lost work besides frictional losses. An optimal Lift-Span Tech configuration minimizes lost work through the aft control surface. The extent of lost work from upper and forward surfaces tends to be specific to modes of operation. Beyond fences, the ground, and the trailing taper, the following technologies can also reduce lost work:

- Use of morphing upper surfaces optimized to reduce upward dissipation.
- Distributing propulsion along the chord length of the upper surface.
- prioritizing lift from the lower-surface cavity rather than from the upper surface.
- Transit in tunnels were upper tunnel surfaces block the upward dissipation of lift force.

Separate studies were performed on the [gain]:[loss] analysis of increased L/D efficiency versus lost propulsor thrust identified that the ratio of gain to loss can exceed 8:1 initially, but asymptotically approaches a 1:1 tradeoff as propulsor power increases [21]. The lost-work analysis of Table 4 agrees with this trend. Ducted fans and jet engines can attain a maximum in efficiency with scoop-type intakes and bell-nozzle discharges when removed from a lifting body. As a lifting body surface approaches and connects to the optimal isolated engine design, the optimal design varies with the lifting body surface configuring for optimal asymmetric intake and discharge surfaces. The size of the lifting body and any ground effect will influence that optimal design.

Induced Drag – Typically accepted advantages of WIG aircraft include higher speeds relative to maritime alternatives and increased lift with shorter wingspans. Increased L/D efficiency of WIG aircraft is complicated by the tradeoff of decreasing efficiency with shorter wingspans and requirement to travel near ground level. While increased induced drag is associated with WIG aircraft, the arguments lack definitive verification since induced drag is coupled with lift and L/D efficiency tends to be a more accurate characterization [16, 15].

For GEM induced drag is prevalent; often an artifact of how the void of air created by WIG translation is primarily replaced from flow over the upper surface resulting is expansive lower pressures on the entire upper surface of the GEM sections. GEFT GEM designs overcome the induced drag by using increases in pressure from the Lift Span Tech propulsor to substantially eliminate lift pressures on the trailing taper.

Control Surfaces – WIG designs tend to have large secondary lift surfaces, such as horizontal stabilizers, to provide control. Halloran and O'Meara attribute the need of larger control surfaces to how the moment coefficient of ground effect vehicles is a strong function of pitch (i.e., a tendency for the nose to flip up during flight) [14]. Different dynamics exist with adjustable fence control algorithms and Lift Span Tech which impact lift on the aft half of the upper surface.

When vertical movement of fences is distributed to multiple sequential fence sections, upward movement of fences can selectively reduce pressures on sections of the lower surface. This enables approaches to both pitch and roll control beyond that used by WIG vehicles.

More-detailed studies revealed that control of trailing flap sections can provide additional degrees of control, which included an application-specific condition where optimal efficiency was at a flap extension about 67% of the fence extension. The cavity pressure is a steady-state condition. The fence clearance control loss of pressures based on the clearance and the cavity pressure. An increasing flap clearance increases the flow into the cavity which can lead to an optimal flap extension different than the fence extension.

Conclusions

The ground effect machine (GEM) is a term which refers to lifting-body vehicles capable of both hovercraft and WIG performance. A barrier to the advancement of GEM is the perception that increasing L/D efficiency correlates with decreasing [clearance]:[chord] for the lifting body where the necessary length to achieve passenger-size cabins is extreme. The Lift Span Tech configuration is used on GEFT designs and is able to truncate chord length and realize high L/D efficiency at reasonable chord lengths and favorable [thickness]:[chord] for passenger travel.

A lost work analysis around a GEFT lifting body identified that: a) increased L/D efficiency from ground effect can be attributed to no streamline loss of energy on the lower surface, b) Lift Span Tech is able to significantly reduce non-thermal lost work exiting the trailing surface, and c) the leading surface is substantially at the control free-stream condition without flow of lost work. This lost work analysis agrees with CFD results identifying significant improvements in L/D efficiency are possible and practical with GEM with: a) Lift-Span tech and b) fences used as control surfaces to control lift pressures in the lower-surface cavity.

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