Ground Effect Flight Transit (GEFT) in Subways

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Abstract

Extending the flight corridors of ground-effect flight transit (GEFT) from above-ground railway tracks to subway tunnels could ultimately allow improved access throughout cities for both commuter and intercity transit. Since GEFT do not have undercarriages, the opportunity exists to increase capacity by converting single-lane tunnels into upper and lower lanes with resulting evolution toward high-speed non-stop subway service.

The digital prototype simulation of GEFT aircraft in tunnel corridors identifies that high efficiencies are attainable with flight in corridors at half the height of most subway systems. A critical analysis identifies that energy consumption is sufficiently low (e.g., from 10% to 25% of the energy for helicopter transit) so as to be of negligible cost relative to the value of reduced transit times and reduced infrastructure depreciation for this transition. The inner-city subways would evolve to being part of a trans-modal network of railway, subway, highway, waterway, and greenway transit for high-speed non-stop intracity, intercity, transcontinental, and intercontinental transportation.

Introduction

Subways provide good access throughout many cities, and so, trans-modal ground-effect aircraft capable of engaging subway tracks could offer a path of transit evolution with exceptionally low energy consumption and low money-value-of-time using existing infrastructure. Since ground-effect flight transit (GEFT) vehicles do not have undercarriages or wheels, the prospect exists to split single-track tunnels into two over-under tracks, and therein, enable new standards of non-stop high-speed commuter transit.

GEFT provides a leapfrog advance in capabilities due to a novel hovercraft-like cavity which uses air's dynamic pressure to provide L/D efficiencies in excess of 50 over railway tracks in open air. Performances are based on digital prototype simulations using OpenFoam and SimFlow software. A critical analysis using basic principles of physics confirms the efficiency and paves the way for more-sophisticated lost work analyses to evolve application-specific configurations.

When adding the tunnel constraint to GEFT, three advantages for creating high L/D for ground effect flight emerge:

- **a)** Enhancing lower surface vehicular lift by engaging the tunnel's lower surface (as with ground effect aircraft).
- **b)** Enhancing of upper surface vehicular lift pressures by engaging the tunnel's upper surface.
- **c)** Ability to use the entire circumference to place fences to block lateral loss of lift pressures.

A disadvantage to overcome is:

- **a)** The vehicle's tendency to push air through the tunnel creates higher pressure in front of the vehicle and lower pressures behind the vehicle; this increases form drag.

This paper evaluates a series of airfoil simulations in tunnels to identity the extent to which high L/D efficiencies can be part of a trans-modal GEFT network to realize advantages of reduced energy consumption, reduced transit times, and reduced infrastructure costs. The technology can use existing corridor infrastructure for initial applications with incremental infrastructure evolution as a path forward.

Background

This is the fourth of the following series of papers for which research prepared in June and July of 2024: [1]

1. New Benchmarks in Ground-Effect Flight Energy Efficiency [2]
2. Ground Effect Flight Transit (GEFT) – Approaches to Design
3. Ground Effect Flight Transit (GEFT) – Towards Trans-Modal Sustainability
4. Ground Effect Flight Transit (GEFT) in Subways

A science and technology background for this paper can be found in available papers 1-3. That background is the groundwork for the following paper on tunnel transit and impact of pressure on L/D efficiency.

Tunnel Transit – Tunnel and tube transit typically fall into three categories:

- Wheel-based trains or cars passing through tunnels with entrances open to the surroundings.
- Pneumatic transit where air pressure pushes vehicles or cannisters through tubes.
- Isolated low-pressure tunnels, like hyperloop, claiming advantages of high energy efficiency from a massive reduction in aerodynamic drag.

This paper is on a fourth type of transit through tunnels with the indicated three categories:

- Ground-effect aircraft transit (GEFT) flying through tunnels.
  - **a)** Transit with net air flow in the direction of vehicle travel.
  - **b)** Transit with essentially zero air flow through the tunnels.
  - **c)** Transit with air flowing in the direction opposite the vehicle travel direction.

Category "c)" is the result of all thrust being provided by electric fans, or similar air-momentum based propulsion, on the vehicles; the sources of propulsion are referred to as "Sources" within this paper. It has the disadvantage for any following vehicles of creating a headwind in the tunnel that decreases efficiency, and in general, is only reasonable for shorter tunnel corridors with vehicles operating at high L/D efficiency.

From an optimization perspective, category "a)" is the lower velocity limit of category "b)". The upper velocity limit of category "b)" is for vehicles traveling solely on wheel friction or magnetic forces with a surface in the tunnel. The span between these upper and low limits uses a combination of Source propulsion and tunnel-surface-based propulsion.

Because Sources can be positioned and designed to increase the L/D efficiency of aircraft with net gains in reduced drag versus costs in reduced Source thrust, an optimal energy efficiency uses a combination of Source propulsion and tunnel-surface-based propulsion. The non-trivial identification of the optimal combination of these two propulsion mechanisms would include the following factors:

- The extent to which Sources on the vehicle increase the L/D efficiency of the vehicle.
- Viscous and pressure drag on the vehicle,
- Viscous drag on the tunnel walls.

- Mechanisms and efficiency for direct use of grid electric power and the benefits thereof.
- Impact on infrastructure costs such as tunnel diameters.
- The type, weight, and cost of energy storage on the vehicle and whether that energy is used or charged during tunnel transit.
- The impact of high air velocities in tunnels on subway stations and the people exposed to those air velocities.

This optimization is not a part of this paper. A likely optimal is near 90% of the thrust being provided by Sources on the vehicle since Sources on vehicles can reduce drag and thereby reduce the thrust requirements.

Impact of Pressure on L/D Efficiency – Drag on an aircraft can be broken down to either pressure drag or viscous drag, and this is the breakdown typically calculated and computed by CFD software. For typical tube-and-wing aircraft a high viscous drag contribution from the fuselage leads to advantages of reduced total drag at lower pressures of higher altitudes. A standard perception emerges that lower pressures are needed to attain higher efficiencies.

GEFT dynamics varies in two ways from the basis for the standard perceptions:

- For lifting-body GEFT designs, the same surface pressures produce lift and drag with a general absence of a significant viscous drag contribution.
- Efficiencies are so high at atmospheric that there are significantly diminishing returns for further increases in efficiency.

A conclusion emerges that the lost work associated with attaining higher altitudes can readily be more than the energy saved from flying at those higher altitudes. That lost work includes energy spent taxiing on airports and extra miles of transit in queue for landing.

A similar conclusion emerges on transit in lower-pressure tunnels; specifically, optimal pressures are higher for GEFT in tunnels than assumed for hyperloop-type concepts.

A conclusion is that GEFT used in the next few years on existing railways, subways, highways, waterway, and greenways could be part of an evolving incrementally expanding infrastructure with higher velocities than subsonic jets and without the time and money spent accessing airports. The benefits provide a path forward with significant reductions in energy, time-value-of-money, and infrastructure costs; that path forward would be covered by the free market or government intervention based on the dynamics of the market due to significant performance advantages of alternatives.

L/D Efficiency – This paper extends L/D studies of previous papers in this series to include travel in tunnels.

Figure 1 shows the pressure profiles for a 3D model based on an airfoil designated "Airfoil B" with an exceptionally high L/D ratio of 53. Key features of the pressure profile that correlate with good performance are: well-formed leading and trailing stagnation points, a lower cavity pressure near air's dynamic pressure throughout the cavity, and a relatively continuous pressure gradient on frontal and trailing surface; that pressure gradient decreases from lower stagnation points to upper-surface lower pressures.

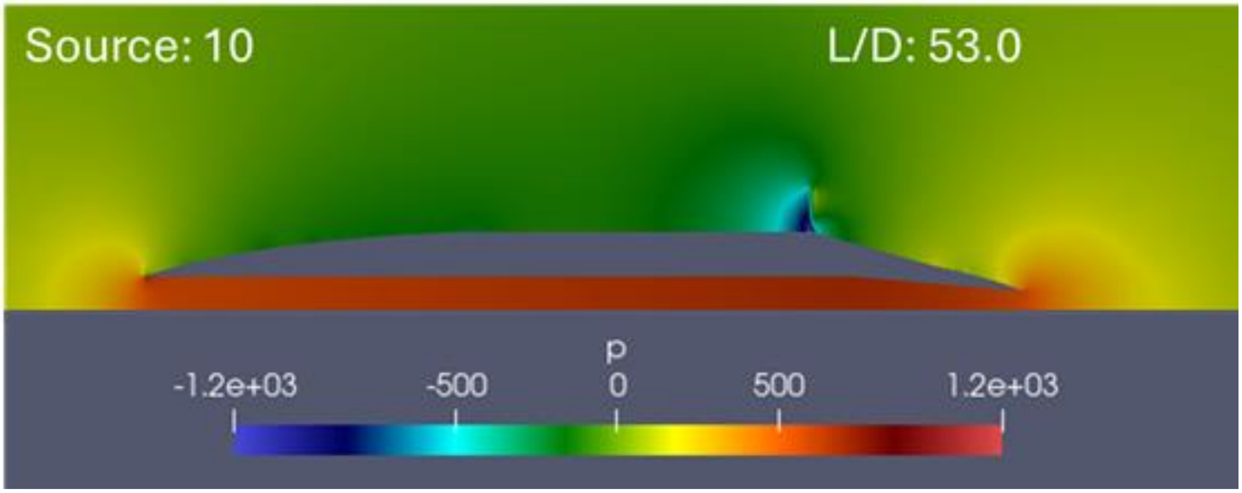

Figure 1. Example of a high L/D benchmark pressure profile. A cross section of a 3D prototype simulation using fences to block losses of lower compartment lift pressures. Free stream velocity is 40 m/s and the Source is in m^4/s^2.

The advances of the research of this paper are founded in using computational fluid dynamics (CFD) to identify simple explanations of how air flow generates lift pressures on lifting bodies. The simple explanation consists of principles well-founded in physics, one principle being that surfaces are able to modify the development of pressure profiles. Like fences, the ground is important enable the attaining of L/D efficiencies in excess of 50, which is 3X the efficiency of airliners and more than 6X the efficiency of helicopters and multicopters.

At these high efficiencies, battery power and direct electric power reduce energy costs to being tertiary in importance as compared to the time-value-of-money in transit and annualized infrastructure costs. GEFT technology can use existing infrastructure to achieve record high transit L/D efficiencies, and therefore energy efficiencies, with low transit times.

In subway tunnels, distances are typically less than 10 miles and direct transfer of grid power to the vehicle is an option. Efficiency is less important than in free flight and inter-city transit where lower efficiency reduces ranges and requires that more payload be replaced with batteries or fuel.

The goal of this paper is to identify L/D efficiencies for GEFT vehicles in tunnels and to identify if that efficiency is sufficient to realize opportunities for advantages in reduced energy consumption, reduced transit times, and reduced annualized infrastructure costs.

Methods

Digital Experiments - OpenFoam and SimFlow CFD software were 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~~. No 3D simulations are reported in this paper. Unless otherwise reported, the scale chord of the STLs were 1 m, the fluid was air at 1 atm pressure, and the free stream velocity was 40 m/s.

The ground was simulated as a lower boundary condition “walls” having a velocity equal to the free stream air. Tunnel simulation was simulated in 2D using walls as upper and lower boundaries. Propulsion sources were simulated as cubical geometries that generated horizontal velocities based on the power setting.

Figure 2 provides example CFD meshes which is the initial step in CFD simulation. The meshes illustrate the ground, tunnel’s upper surface, and Sources.

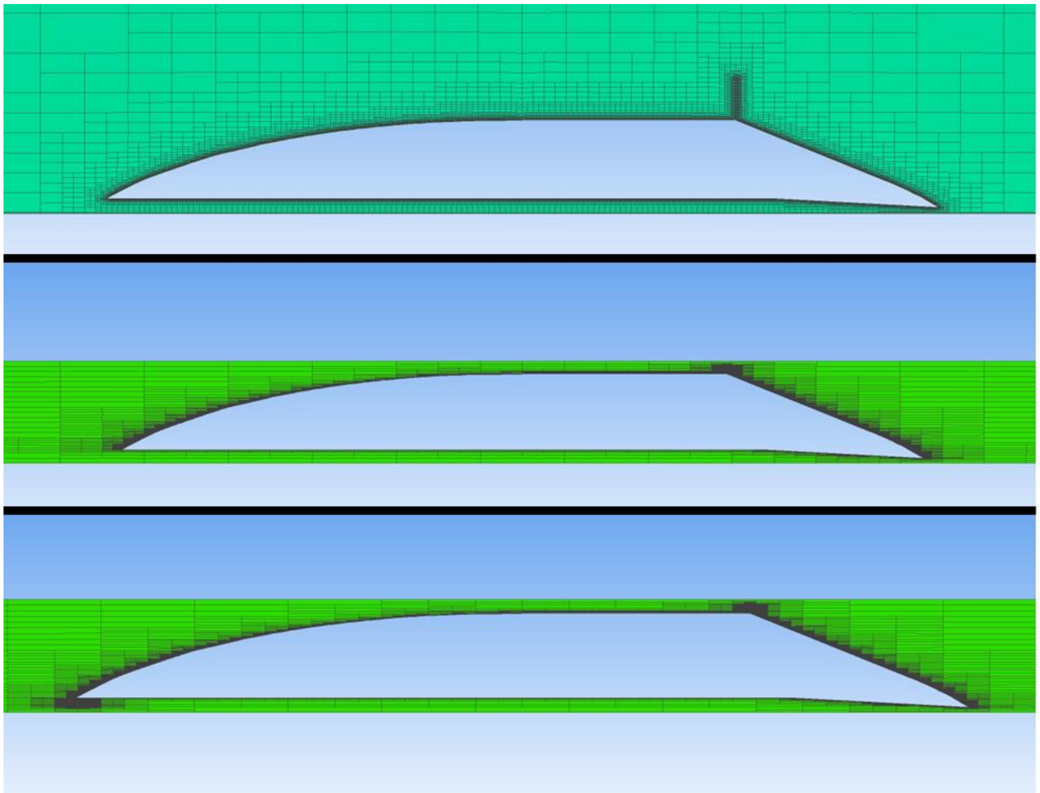

Figure 2. CFD meshes for 0.1 t/c airfoil of 1 m length with one upper Source 0.05X0.005 m Source (upper) with 0.004 m clearance to ground, one upper Sources in tunnel of 0.004 m upper and lower clearances (middle), and upper and lower sources of 0.01X0.005 m Sources. Cavity height is 0.01 m.

Figures 3 and 4 illustrate the STL, with dimensions, used to generate the 2D mesh. Figure 4 illustrates an example Airfoil (i.e., 2D cross section) of the Figure 3 STL. An airfoil, designated “Airfoil B”, was used in 2D simulation of ground-effect and tunnel-effect transit. The scale as 1 m in length and 0.1055 m in height includes a 0.01 m cavity height. The Source was 0.05 m X 0.005 m for ground-effect and 0.05 m X 0.001 m for tunnel effect. Clearances were 0.006 m. Figure 2 provides the meshes for the 2D simulations which show the upper and lower walls of the simulation.

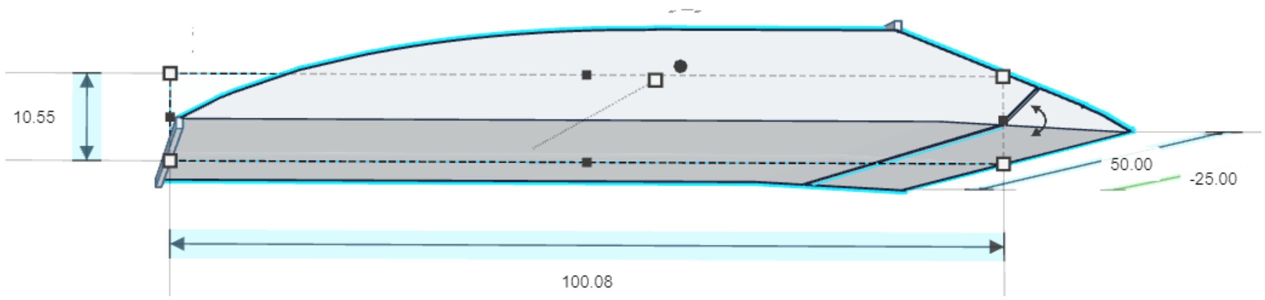

Figure 3. Illustration of computer-aided design (CAD) STL file (standard template library) of lifting body with upper and lower sources and a trailing section bypass from the cavity (height = 0.01 m) to the upper surface of the trailing taper. Dimensions are in cm.

Figure 4. A 2D airfoil of the Figure 3 STL file.

Results from CFD simulations (i.e., experiments) include: lift coefficients (C_l), drag coefficients (C_d), L/D (equal to C_l/C_d), pressure profile images, and velocity profile images. Flow around wheels on the vehicle is not considered under the assumption that air flow can be streamlined between fences and wheels.

All pressure profiles of this paper use a pressure color plat with equal positive and negative magnitudes. This allows conclusions to be drawn from pressure profiles without attention to the magnitude. Vivid red is always higher pressure (relative to free stream pressure), vivid blue is lower pressure, and lime green is free stream pressure. The pressure is reported as P/ρ in units of m^2/s^2.

2D CFD studies are referred to as “airfoil studies”. Airfoil have reduced computational times and are easier to interpret. Also, the use of fences allows the performance of lower surface pressures of 3D prototypes to approach the pressures and performance of the airfoils. The 2D airfoils were used to refine designs with subsequent verification with 3D prototypes.

The Results section follows the sequence of studies in this research; wherein, both that sequence conveys the basis on which design choices were made. The goal is both an understanding and a down-selection toward conclusions.

For transit in tunnels, the CFD software may generate results that include pushing of air through the tunnel which is characterized by different pressures at the ends of the tunnel in the CFD mesh. The solution process used in this paper is to converge on vehicle Source settings until the pressures distant from the vehicle are equal in the leading and trailing directions such as illustrated by Figure 5.

Figure 5 illustrates a color scale for pressures. The color scale may vary between images; however, the positive and negative magnitudes for the pressure scales are kept equal and opposite. This translates to a lime-green color of zero pressure (P (m^2/s^2) = pressure divided by air’s density, air is at 1 atm).

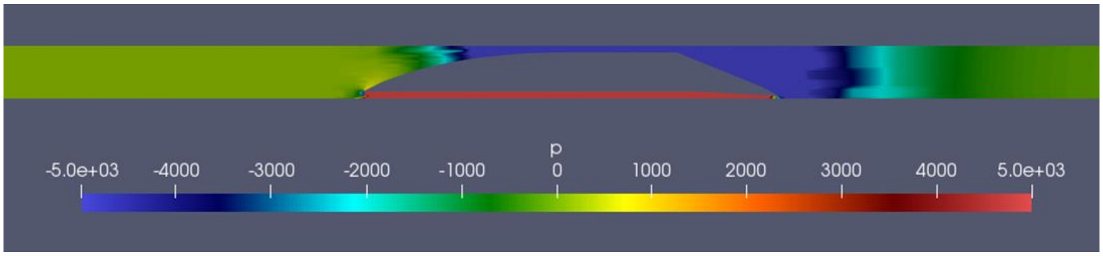

Figure 5. Illustration of relaxing of pressure aft the vessel with an expanded scale for the transit at a Source setting of 5.0 m^4/s^2.

Results

Tunnel effect simulations of airfoils (2D simulations) are summarized in Table 1 and Figures 6 through 8. Earlier results identified that the pressures in the lower cavity of a GEFT of 3D simulations approach 2D simulation results at low clearances (i.e., ratios of clearance to vehicle thickness of <0.005). [1] In tunnels and with use of fences on the upper surface, the L/D of 3D prototypes will approach the Table 1 results with low fence clearances.

Table 1. Summary of Source settings and clearances of 2D airfoil simulations. The lower clearance is the lower wall location. The upper clearance is the upper wall location minus 0.115 m (vehicle height plus 0.01 m for Source height.

	Airfoil Descriptor	**L/D**	**Source (m^4/s^2)**	**Wall Locations (m) Lower, Upper***
a.	Trailing Spoiler	28.0	S=1	-0.004, .215
b.	Trailing Spoiler	23.6	S=2	-0.004, 0.165
c.	Trailing Spoiler	20.0	S=2.5	-0.004, 0.165
d.	Two Spoilers	12.6	S=3	-0.004, 0.165
e.	Two spoilers, Version B	20.4	S=2	-0.004, 0.165
f.	Two spoilers, Version C	22.9	S=2	-0.004, 0.165
g.	Upper & Lower Source	25.5	S=1, S=0	-1.0, 1.115
h.	Upper & Lower Source	28.0	S=1, S=3	-.010, 0.315
i.	Simple Bypass	23.0	S=1.7, S=2.5	-0.004, 0.125
j.	Slanted Bypass	16.0	S=2, S=3	-0.010, 0.125
k.	Diffuser Bypass	20.2	S=0, S=1	-0.004, 0.165
l.	Diffuser Bypass + Spoiler	14.5	S=0, S=2.5	-0.004, 0.165
m.	Spoiler 2	12.0	S=2, S=2	-0.010, 0.125
n.	Cavity Bypass	12.6	S=2, S=3.5	-0.010, 0.125
o.	Cavity Bypass 2	7.0	S=1.5, S=4	-0.010, 0.125
p	Cavity Bypass 3	28.3	S=1, S=3	-0.01, 0.125

An inspection of the Table 1 reveals the L/D are consistently less than 30. The sequence was in the chronology of the experiments and included adapting the design from sequential results. For all but the final result, values of L/D in excess of 20 correlated primarily with either the upper or lower clearance being greater than 0.01 m. Lower L/D for these tunnel simulations can be attributed to having to push air around the airfoil to avoid pushing air through the tunnel.

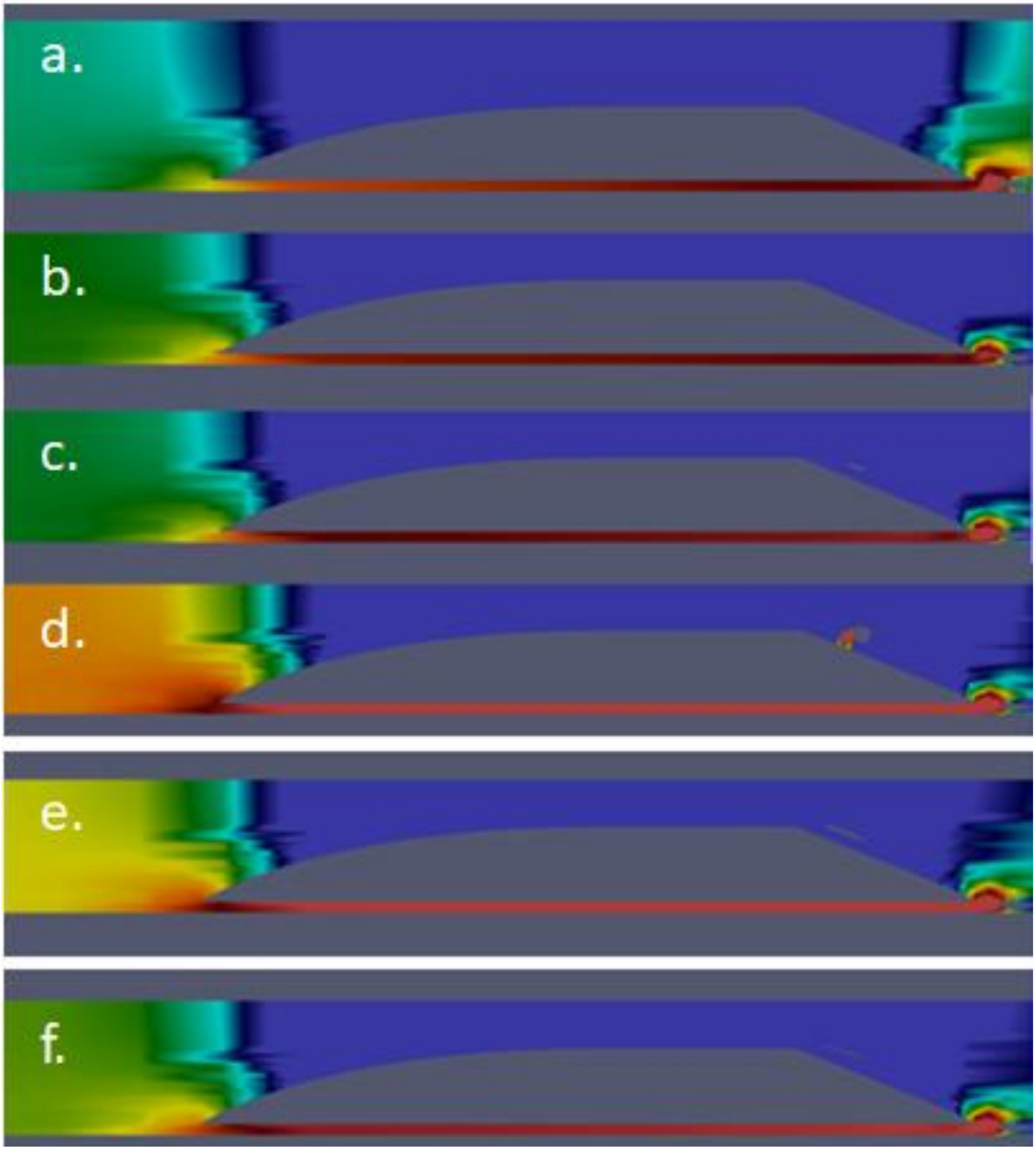

Figure 6. Pressure profiles of converged pressure profiles in tunnel with different upper clearances and different versions of spoilers.

Figure 6 illustrates a persistent lower pressure region above the trailing flap. When good pressure gradients form at the leading section (i.e., pressure gradient with predominance of lower pressures), the predominance of lower pressures on the trailing taper result in increased form drag and decreased L/D.

Various spoiler designs were used to increase L/D. One spoiler option was to extend-rearward the flap section below the vehicle's lower surface to create a gap. That flap/spoiler forms a trailing stagnation pressure point and that pressure expands upward along the trailing taper. The spoilers were effective, improving L/D by about 10%.

Various geometries of a second spoiler were placed above the trailing taper, near the airfoil's upper surface. The spoilers increased pressure above the trailing taper, but the spoilers formed their own trailing-section form drags. Normally that trailing section from drag would not be significant; however, when pursuing L/D in excess of 30, the drag becomes more significant.

Figure 7 illustrates various options to use a bypass duct, with a Source, through the airfoil to force air dynamics and pressure profiles similar to those of Figure 1. All of these Figure 7 studies were without Sources at the leading section of the lower cavity. Only the ducts with a diffuser discharge produced good pressure profiles in the lifting body's lower cavity.

Figure 9 illustrates how a diffuser and the absence of a taper can enable a diffuser to convert discharge velocities to pressures on trailing surfaces. Whereas a jet engine has lost work in the form of high-velocity discharge to the surroundings, a diffuser at the duct exit converts the velocity remaining in the air stream to surface pressure and has reduced lost work.

As an alternative to a bypass duct taking in air on the lifting-body's frontal section, a bypass duct could have an entrance in the cavity. Pressure profiles m-p (Figure 8) illustrate four options for a bypass duct with entrances in the cavity. The Figure 8p pressure profile stands out as having good lift pressures on upper and lower surface near air's dynamic pressure magnitude of 800 m^2/s^2. The Figure 8o bypass is similar to the Figure 8p bypass, only the duct is higher; that duct releases too much of the lower cavity pressure

The Figure 8p bypass is the one illustrated by Figures 3 and 4. The L/D of 28.3 provides a basis for Discussion. Degrees of freedom to further increase this L/D include:

- Optimization of the duct area and flow.
- Use of a diffuser duct ends to reduce lost work at those ends.
- Increase in lower surface clearance slightly so as to use the lower cavity more-effectively to push air from the front to the back of the vehicle.
- Use of spaces and properly engineered surfaces to bypass air around the sides, including results-driven optimization of this bypass.
- Increase the effective pitch of the lower surface, which is 0.57° based on a cavity height of 0.01 m.
- Reduce the pitch of the trailing taper

In view of these design degrees of freedom, L/D in excess of 30 should be readily attainable.

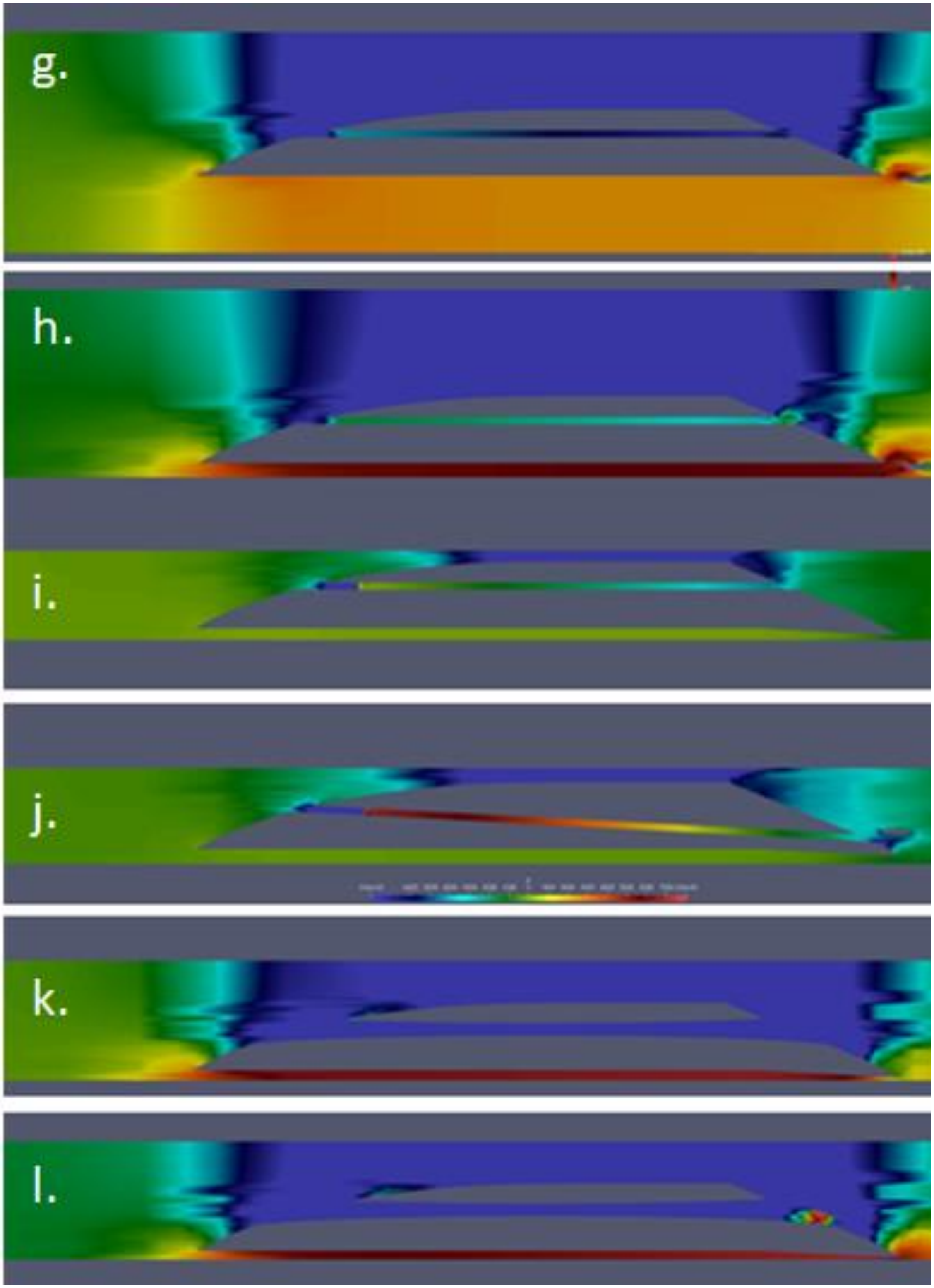

Figure 7. Pressure profiles of converged pressure profiles in tunnel with different clearances and front-to-back bypass duct with bypass Sources.

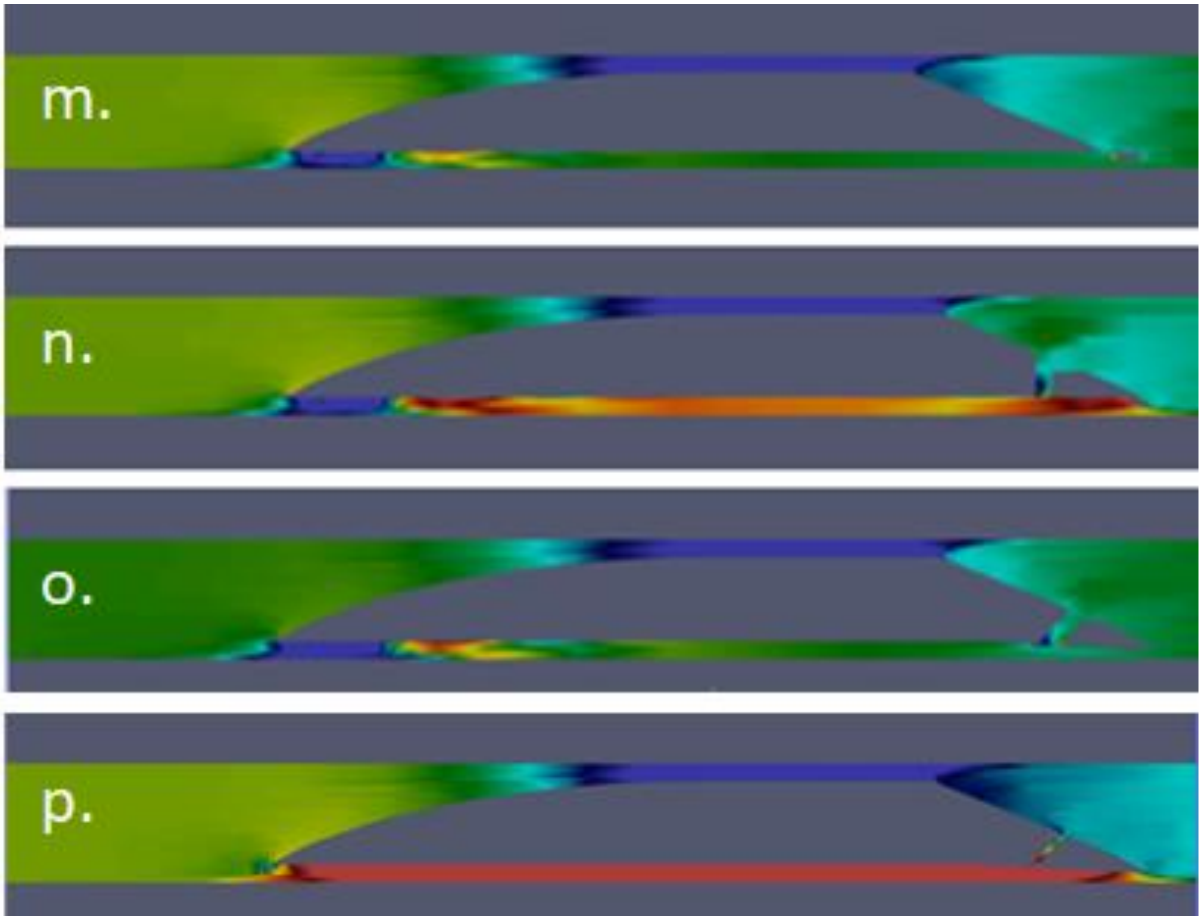

Figure 8. Pressure profiles of converged pressure profiles in tunnel with different clearances and front-to-back bypass with bypass Sources.

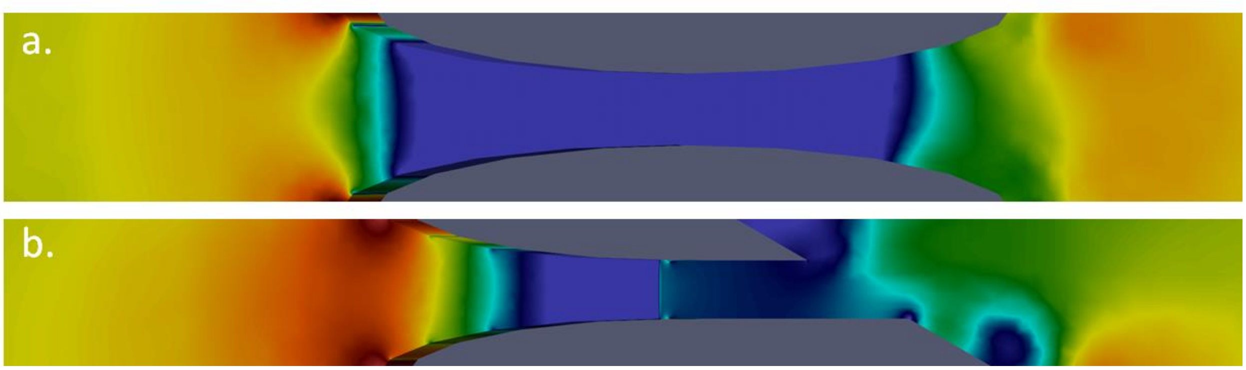

Figure 9. Pressure profiles of front-to-back bypass ducts with vertically-symmetric diffuser discharge (upper) and discharge to upper surface of taper.

Simulation of Airfoil Increased Effective Pitch of Lower Cavity – The effective pitch of previous airfoils where at 0.57° with prospect of attaining L/D in excess of 60. The airfoil (2D) of Figure 10 was simulated in ground effect extended to tunnel effect (with upper surface). Simulation results are provided by Table 4 and Figure 11. The effective pitch of the upper Lift Span is 1° and the effective pitch of the lower cavity is 1.14°.

If the bypass is too large (e.g., too great a height), it effectively bleeds lift pressure from the lower cavity. The size and shape of the bypass can be treated as a result-driven variable. The Figure 10 airfoil is to scale with the bypass have a height of about 0.7% of the vehicle height.

Figure 10. Airfoil with upper and lower Sources and a duct connecting the cavity to the trailing taper. The cavity run to rise (i.e., drop) is 100 to 2 for an effective pitch of 1.14°.

Table 4. Lift coefficient, drag coefficient, and drag pressures of airfoil of Figures 10 and 11. Note, the lift and drag coefficients are not adjusted to the correct area; actual values are about 3X the indicated values. Sources are upper and lower Sources in m^4/s^2.

L/D = 31.5	S_U =3	Cm: 0.2217	(pressure: 0.2217	viscous: 1.514e-006)
	S_L = 8.5	Cd: 0.01326	(pressure: 0.01206	viscous: 0.001192)
		Cl: 0.4188	(pressure: 0.4187	viscous: 7.288e-005)
		Cl(f): 0.4311		
		Cl(r): -0.01231		

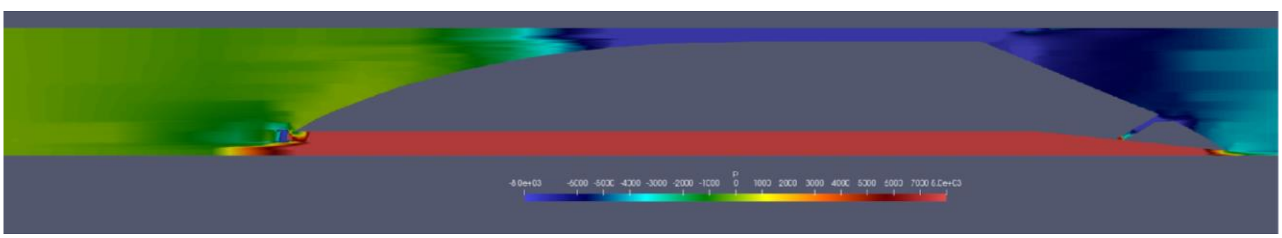

Figure 11. Pressure profile of airfoil of lifting body with bypass connecting lower cavity to trailing taper.

Figure 12 illustrates a ground effect lifting body having a leading edge, a horizontal lower surface extending aft-ward from the leading edge, and an upper surface extending aft-ward at a pitch between -80 and 10°; where the horizontal lower surface is an upper surface of a lower cavity of the lifting body. The following are aspects of additionally refined versions of this basic vehicle:

- The upper surface is convex upward.
- The vehicle includes a Lift Span, an upper surface trailing section propulsor, and a tapered trailing section.
- A trailing edge flap, or similar surface, which is configure to convert air's dynamic pressure into surface pressure, aft the horizontal lower surface.
- A lower-surface propulsion Source near the leading edge, said lower-surface propulsion source configured to increase air flow in the lower cavity.

A spoiler can help alleviate boundary layer separation and may be used as a control surface; especially as a surface similar to an elevator stabilizer of a airliner tail. Here, the ground effect lifting body comprising a trailing section taper and a spoiler aft the upper surface of the trailing section taper. The spoiler may be located below and aft a trailing edge of the trailing section taper. The spoiler may be a control surface for controlling the center of lift of the lifting body. The spoiler may extend and retract from a contiguous interface with the lifting body (i.e., the spoiler is a flap that may extend to form a gap between the flap and the lifting body).

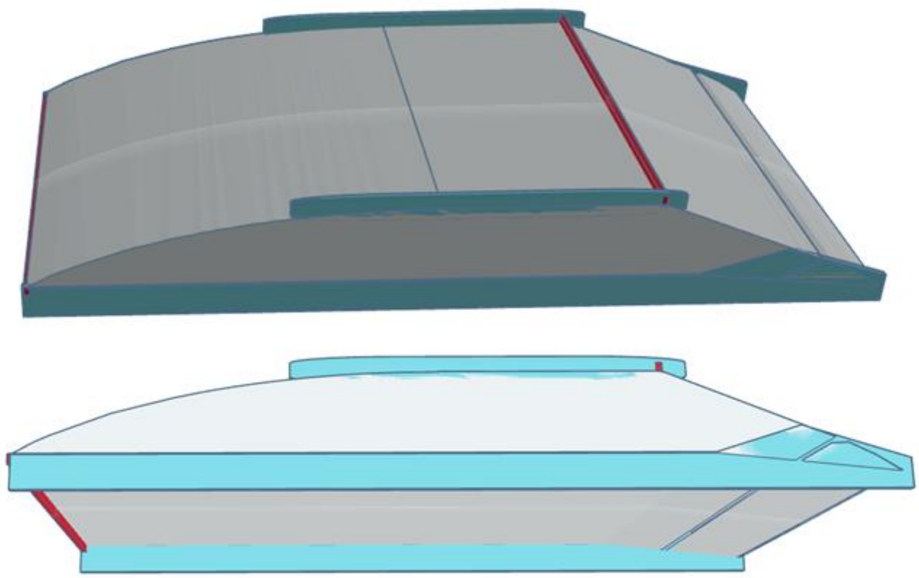

Figure 12. Two views of lifting body illustrating upper and lower fences of upper and lower cavities, upper and lower Sources, and a bypass duct from the lower cavity to the trailing taper.

A bypass duct may help alleviate boundary layer separation. A preferred location for the bypass duct is with a discharge on a trailing taper surface between a trailing edge and an upper surface propulsor and an intake in a lower surface cavity. A diffuser discharge configuration on the bypass duct may convert air's kinetic energy to pressure on an aft surface which increases efficiency. Other options include:

- an intake at the front of the ground effect vehicle,
- the bypass duct containing a Source to accelerate air through the duct,
- configuring the ground effect lifting body for travel in tunnels where a part of the bypass duct's wall me be the side of the ground effect vehicle and wherein part of the duct's wall is the side of the tunnel,
- an upper surface cavity extending between upper surface side fences aft-ward to a trailing object of lower pressure generation (That trailing object could be a propulsor, that trailing object could be a surface of pitch between 4° and 30°. The upper-surface cavity has an effective pitch between -2° and 2°, more-preferably between -1° and 1°.), and
- configuring the bypass duct to reduce the propensity to form boundary layer separation above the trailing taper.

Preferred fences are vertical, except in tunnels where lateral extensions of constant span may serve as both fences and wings. These wing fences: a) would have similar effective pitches of the near-horizontal surfaces they laterally extend, b) would approach parallel side tunnel walls in close clearance, and c) could have control surface areas. Between an upper pair of fences and a lower pair of fences ducts could form with the side wall, including Sources and diffuser surfaces on the trailing section to transform velocity into pressure on aft surfaces.

Discussion

Based on 2D simulations of GEFT flight in tunnels, an L/D target of 30 should be readily attainable. The question is on the value of attaining higher L/D in tunnels where total travel distances are typically less than 10 miles.

Table 2 puts this energy efficiency in perspective to other forms of transit where GEFT Subway uses 80% less energy than helicopters and about 40% less than the U.S. average for light rail. Energy costs would be 4 cents/mile and could be provided by 100% renewable electrical power with very low carbon footprints.

Table 2. Comparison of energy efficiencies. [3-6]

Contemporary Vehicles	L/D	Estimated (Btu/passenger-mile)
Multicopters	5	6459
Helicopter	6	5383
Cessna 172	11	2936
Short-Haul Flight		3472
Car		2569
Airliner	15	2153
U.S. Commuter Rail		1583
Bus		1389
Ferry		264
GEFT railway	52	621
GEFT ratilway+ Source	>60	<550
Target GEFT Subway	30	1100

If GEFT subway service were 90 mph non-stop, the time for a 10-mile commute would be 6 minutes versus a typical subway which would be about 21 minutes. The value of 15 minutes at $20/hour is $5 versus GEFT energy costs of $0.40. Table 3 compares numbers for a 10-mile roundtrip under similar assumptions.

Within the basis of Table 3, including any reasonable variations, the metrics definitively identify that the true value of high-speed non-stop commute at 90 mph resides in saved time and saved infrastructure (i.e., parking lots and highways). Also, when using electric power, the environmental costs of the GEFT transit energy are small compared to the time value of money and infrastructure depreciation.

The metrics do not include first-mile and last-mile costs; however, the assumption is that route planning would make GEFT mass transit first/last mile costs less than for other mass transit. An additional assumption is that solutions like autonomous taxi service will emerge as part of route planning for GEFT mass transit.

Table 3. Cost metrics related to 20-mile roundtrip city commute.

Costs for 10-mile Roundtrip Commute	**Cost**
GEFT Subway Energy, nonstop 90 mph, L/D=30	$0.80
GEFT Subway Energy, nonstop 90 mph, L/D=20	$1.20
GEFT Railway Energy, nonstop 90 mph, L/D=60	$0.40
21-minute subway ride time premium over GEFT Subway	$10
Parking Car Downtown	$10-$20
Fuel cost at $4/gallon, 40 mpg	$2
Car at Government Reimbursement of $0.65/mile	$13
Fuel tax of $0.57/gallon assumed to be 50% of highway cost	$2.08
Air Taxi Commute (helicopter or multicopter) Energy	$4-$6

GEFT features that would enable a 90-mph non-stop commute using existing infrastructure include:

- Non-stop high-speed transfer between railway, subway, highway, waterway, and greenway corridors.
- Real-time routing based on traffic and preliminary route planning for mass-transit ride share.

Air Taxi Comparison –Air taxis have about a 5X increase in energy costs versus GEFT. Air taxis also have major FAA (Federal Aviation Administration) barriers for widespread use over cities and approach restricted air space at many locations. Similar barriers would be reduced or non-existent for GEFT vehicles traveling within a few feet of the ground/water of railway, subway, highway, waterway, and greenway corridors. Here, greenway refers to paths over ditches or select landscape without major obstacle, typically less than a mile, for transfer between transit corridors. It is where the greenways are lacking in city infrastructure that subways provide an effective access alternative.

Interpretation, Hypotheses, and Reversibility – Gliders have demonstrated L/D efficiencies in excess of 50, and the digital lifting body prototype of Airfoil B exhibited L/D in excess of 50 without Source augmentation. A >50X increased expression in lift versus drag suggests that the conversion of air flow to lift pressures must be dominated by reversible processes. ~~In a~~A paper documenting the principles on which this work ~~is based~~ includes~~d~~ the following hypothesis [7]:

> *For a streamline about 0.1 t (thickness) above the airfoil, the following occurs from an energy balance perspective starting as the air approaches the leading section of the airfoil:*

1. Gradients of increasing pressure are crossed, converting kinetic energy into pressure energy (i.e., pressure energy is stored as PV and is typically included in enthalpy terms of energy balances).
2. Gradients of decreasing pressure are crossed, converting pressure energy into kinetic energy.
3. Gradients of increasing pressure are crossed, converting kinetic energy into pressure energy.
4. The process is repeated throughout the chord dimension until pressure gradients are negligible.

The air in the streamlines has the critical role of storing and releasing energy in the forms consistent with the steady-state sustaining of the surface pressures. Furthermore, the transformations within the Equation 6 energy balance along the streamline path are mostly reversible in nature. Hence, the energy balance, as applied to the streamline, identifies a series of stages that reversibly "sustain" the pressure of aerodynamic lift—analogous to how the gas working fluid in a heat engine cycle stores and releases energy.

Aspects of flow that improve streamline reversibility include:

1. Laminar flow patterns instead of turbulent.
2. Streamline conditions immediately aft the airfoil that are the same as free stream conditions.

The latter of these, as well as the stages of the streamline, do not identify downwash as being necessary to generate lift, which appears to be accurate for steady-level flight. This conclusion identifies an error in momentum theories of steady-level flight that rely on downwash.

This reversible process for generating lift sets the foundation for a system-level analysis of aerodynamic lift using the control volume …

This hypothesis is augmented based on the high L/D attained with Airfoil B:

A pressure gradient between adjacent streamlines aft an airfoil is not lost work if the transfer of that pressure between streamlines is not turbulent and completes the cycle for each of those streamlines by allowing the separate air control volumes to return to free stream conditions.

The cumulative hypothesis allows airfoil performance to be interpreted and checked by comparing the interpretation with basic physical principles. If accurate, the cumulative hypothesis provides insight into how to make incremental changes in conditions and designs to attain reversible ultra-high L/D efficiency and suggests the following approach to achieve L/D>30 in tunnels with upper and lower clearances of 10 cm:

1. Use of vehicle shape to direct airflow around the sides if the vehicle to substantially and reversibly increase flow around vehicle sides.
2. Augment vehicle shape with forward fans and aft-ward diffusers to create a leading-edge stagnation point immediately below the vehicle's leading edge and a trailing-edge stagnation point behind the vehicle's trailing edge.
3. Adjust a combination of forward lower-surface fans and aft-ward upper-surface fans to create lift pressures in magnitude of 90% to 100% of air's relative dynamic pressure over/under horizontal surfaces.

4. Repeat 1-3 until convergence is achieved.
5. The slope of the trailing taper can be lowered to increase L/D efficiency at the expense of increasing vehicle length.

The 4-step process is based on the concept of reversible processes of air in streamlines and the pressure gradient that exists between the upper surface and the lower stagnation points on both the forward and aft surfaces.

It is suggested that this procedure can be used to achieve L/D>30 in tunnels, but the major advantages associated with trans-modal transit are reduced transit times and reduced infrastructure depreciation; both of which are achieved at L/D=20 in tunnels. Considerably higher L/D are possible over open-air railway tracks as demonstrated by digital prototype performances.

Evolutionary Pathways – Due to the diversity of corridors and the design options, the trans-modal GEFT systems of this paper have many paths of evolution. Especially high impact design options on that evolution are:

- Transit through tunnels at low profile that allows doubling the amount of transit corridors in existing subway and tunnel systems.
- Low-cost overpass routing and intersections in cities where stoplights and stop signs are eliminated.
- Extension to longer-distance tunnels that use Bernoulli Loops and tail winds to enable velocities greater than used with commercial airliners. [8]

Conclusions

To attain L/D efficiencies greater than 20, tunnel-GEFT configurations must utilize additional degrees of design freedom than needed with GEFT over open railway tracks. Implicit degrees of freedom for tunnel transit are: a) upper clearance, b) upper fence dimensions, c) lower clearance, d) lower fence clearance, and e) base airfoil shape such as Airfoil B. The additional design degree of freedom is an engineered bypass of air to avoid excessive pressure build up of air through the tunnel. The suggested bypass is around the sides using surface shapes approaching reversibility of the air flow and fans to adjust the magnitude of by-pass air flow. While the digital twin simulations of this paper were only able to achieve L/D near 30 when flying with low upper and lower clearances, a hypothesis identifies that reversible performance can be approached with considerably higher L/D.

From a practical perspective, major benefits of GEFT tunnel transit are achieved at L/D greater than 20 at vertical tunnel spans of 3.3 m. Those major benefits include reduced transit time and reduced infrastructure costs due to including subways as part of a trans-modal corridor network and enabling non-stop transit in subway tunnels by doubling the number of lanes.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: A. Suppes and G. Suppes; data collection: A. Suppes and G. Suppes; analysis and interpretation of results: G. Suppes; draft manuscript preparation: A. Suppes and G. Suppes. All authors reviewed the results and approved the final version of the manuscript.

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