Extended Implications of Racecar Ground-Effect Machines

Abstract

Racecars are the most widely-used ground effect machines, demonstrating the value of technologies like skirts (fences) operating at low clearances to the road. This paper compares the computational fluid dynamics of digital prototypes of race cars with ground effect flight transit (GEFT) vehicles. Whereas conventional explanations like “Venturi effect” fail to explain the pressure profiles, the computational fluid dynamics results are explained by three basic principles of physics, where: 1) impacting air creates higher pressures, 2) diverging air creates lower pressures, and 3) pressure expands at the speed of sound These three basic principles of physics explain how moving a racecar’s front spoiler to the rear of the vehicle transforms the aerodynamics from suction forces on the racecar’s underbody to lift forces on GEFT’s underbody. The pressure profiles are verified by decades of racecar performances including car stability and road-morphology-induced flight. The GEFT applications enable designs of vehicles with substantially reduced rolling losses which result in half the per-per-passenger-mile energy consumption of the best alternatives.

Introduction

Generations of experience and evolution have incorporated world-transforming technologies into routine sights during sportscar racing. That experience combined with new insights into aerodynamics is able to bring forth incredible capabilities, including railcars that cut transit times and costs in half and trucks with energy efficiency high enough for solar panels to fully sustain travel on sunny days [1].

Today, sportscars hug the ground at about 1.2 inches in designs that generate negative pressure pulling down on the car and increasing traction [2-4]. Similar low clearances can be incorporated to preserve higher pressures under lower surfaces—causing the car to fly close to the ground at high speeds like maglev trains, but without the new and expensive guideways. In the past, unstable designs caused sportscars to fly off the tracks in horrific crashes [5, 6]. A technology has now emerged which tames those powerful forces and can transform life as we know it.

The technology is referred to as ground-effect flight transit (GEFT) [7-12]. GEFT have lower cavities similar to hovercraft; but GEFT’s drag-reducing design generates lift forces in the lower cavities. Like sportscars, GEFT have sides that hug the ground; these sides on the lower cavity are referred to as fences and preferably operate at about one inch off the road to block the higher air pressures in the lower cavity from escaping along the sides. GEFT are highly adaptable for different infrastructure. Railway tracks are well-positioned for use with GEFT due to the smooth and level upper surfaces of tracks that enable fence-rail clearances of a fraction of an inch and the freedom to operate at speeds in excess of 100 mph.

In an ongoing competitive initiative, a maglev train route has been proposed between Washington D.C. and Baltimore at a cost near $20 billion to reduce today’s 45-minute trip to 15 minutes [13]. Tomorrow’s GEFT railcars will achieve that 15-minute transit time using existing rails for a small fraction of the implementation timeline and costs. Inter-city transit is one of two mega-markets for this new industry; the higher-impact market is commuter and subway rail where a combination of ground-effect railcars and innovative scheduling methods will reduce commuter transit times to half for an estimated worldwide value savings of over $3 trillion per year due to the money value of time [14].

GEFT can replace petroleum fuels with solar power and set in motion a transformation that stops the cash flow that feeds wars and global warming. Use of petroleum fuels for trucking and air transit have been the most challenging to displace with renewable energy sources; GEFT technology is able to rapidly displace most petroleum fuel with solar power and battery storage.

The paper critically evaluates the aerodynamics that give high performance in sportscar racing and compares the aerodynamics to those used by GEFT with the prospect of transforming transportation worldwide.

The Technology

Figure 1 illustrates unique design features of GEFT. The streamlining of semi-trucks, buses, railcars, and cars converges to a similar design as illustrated by Figure 1. In the sequence illustrated by Figure 1, the following occurs: 1) the fan pushes air over the trailing taper. 2) this fan discharge air flow reduces induced drag behind the car and creates a trailing edge stagnation point, 3) the higher pressures of the trailing-edge stagnation expand forward below the underbody from the trailing edge to the leading edge, and, as a consequence of the higher-pressure region reaching the leading-edge stagnation point, 4) more air is pushed more-upward over the front deflector, creating additional induced thrust at the front section [15, 16]. A low clearance between the fence and the rail, or highway, reduces the loss of higher pressures along the sides and promotes sustained high pressure throughout the underbody which generates aerodynamic lift.

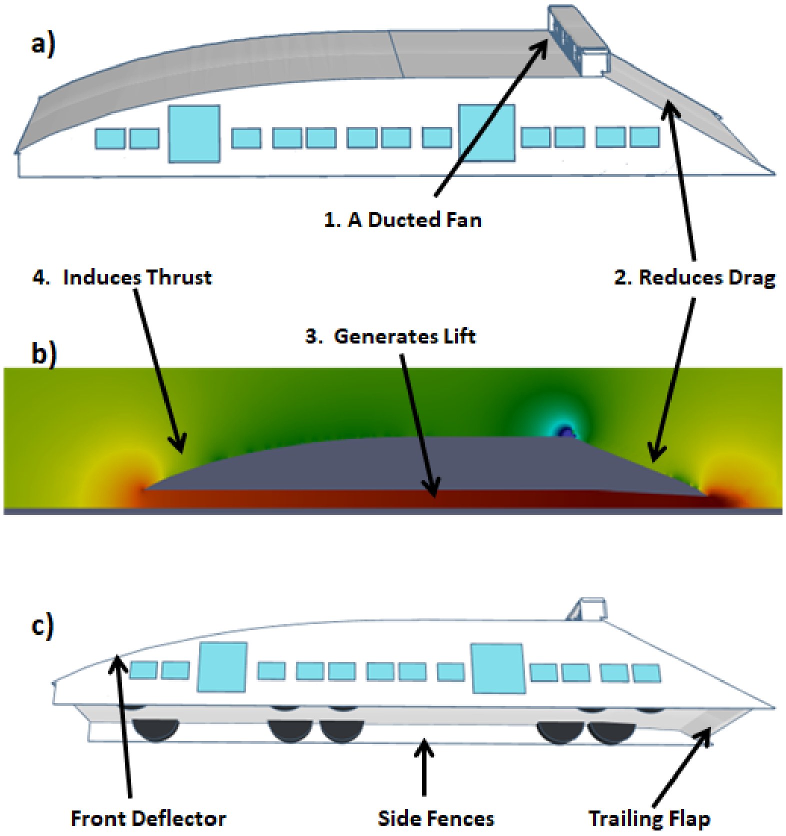

Figure 1. GEFT illustration including car and CFD pressure profiles. Red is higher pressure, blue is lower pressure, and lime-green is zero p_{sig} (see Figure 11).

The same design features that reduce aerodynamic drag, also generate aerodynamic lift. The design differs notably from hovercraft that generate lift in lower cavities, but do little to reduce aerodynamic drag. Some of the performance advantages emerging as a result of the aerodynamic lift include:

- Reduced rolling losses as a result of reduced weight on wheels. Rolling losses are often as high, or higher, than aerodynamic drag losses.

- Higher speeds as enabled by aerodynamic lift which reduces the impact of minor variations in the rails or road and by using control features based on air flow rather than traction.
- Immediate viability of high speeds on railway tracks not suitable for highspeed trains due to lower forces on tracks and use of aerodynamic forces for control and navigation.
- Increased energy efficiency due to ground effect with the road blocking dissipation of lift forces—efficiencies higher than the best airliners or trains.

Analogies with Sportscar Designs

Higher pressures which form at the trailing edge of cars expand at the speed of sound (about 760 mph). That expansion is in all directions which are not blocked by surfaces [17, 18]. In the GEFT's lower cavity, that expansion is against oncoming air, but must reach the leading edge to achieve both the lowest drag and the highest aerodynamic lift. Low fence clearances are critical for these best performances. While those low clearances might seem impractical on roads with speed bumps, the sportscar industry regularly operates at low clearances viably over roads. Railway tracks already meet these tolerances, while interstate highways can readily meet the tolerances if the fence height is coupled to a series of wheels along the side of the car.

Higher pressure points that form at leading and trailing edges of cars are referred to as stagnation points by the aerospace industry. At the front of cars, the stagnation point's pressures push back against the car's velocity in a force referred to as pressure drag. For many cars, the forward pressure drag pushes against a relatively large grill area. For GEFT, the forward pressure drag is on the cusp of migrating from the forward surface to the lower surface, resulting in much lower pressure drag. The pressures of the stagnation point interact with oncoming air, deflecting that air upward. When the air flow diverges from the curvature of the surface, lower pressures form along much of the front deflector surface. These lower pressures on forward surfaces cause "induced thrust." Induced thrust counteracts and subtracts from drag. It is the primary factor in developing the lowest possible drag on GEFT.

A sportscar's windshield forms a second, additional, high-pressure area (see Figure 2) versus GEFT's forward deflector of continuously decreasing surface pitch. An advantage of the sportscar's increase in upper-surface higher pressures is more downward force on the wheels to increase traction.

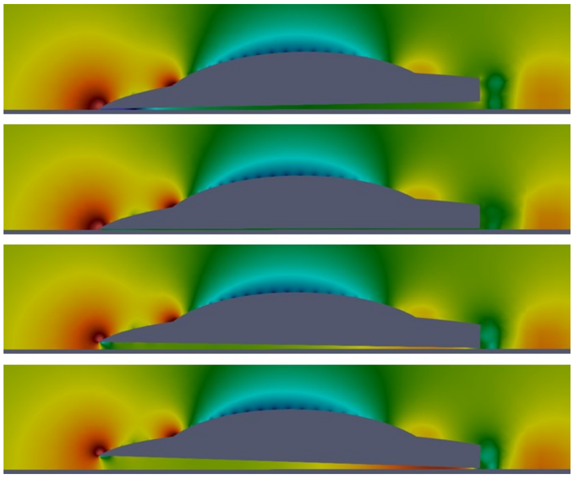

Figure 2. illustration of how pressures which develop from changes in vehicle pitch cause the car to consistently come to rest on the front wheels.

For sportscars, higher pressures that migrate to a lower surface are counterproductive towards traction generation and can lead to the car flying off the road. For GEFT, additional design features tame those higher pressures— as discussed in the next section—to create the desired lift. Typically, an optimal amount of aerodynamic lift supports about 95% of the car's weight with wheels supporting the remaining 5% [15]. Maintaining wheel contact with the ground enables relatively simple configurations to keep the fences in low clearance and to provide some traction.

When streamlining cars for energy efficiency, the impacts of rolling losses are often overlooked. One of the easiest ways to slightly reduce rolling losses is operation at proper tire pressures; flat tires have much greater rolling losses than properly inflated tires [19]. For the railway industry, the minimization of rolling losses has dominated the industry for over a century where steel wheels are used to achieve low rolling losses to allow one engine pull a long train. One of the costs of train operation is the weight and expense of the bogies that support the compartments; heavy duty bogies are necessary to transfer and absorb the multiple ton pushing and pulling forces across the entire train.

By substantially eliminating rolling losses through aerodynamic lift, the dominant driving motivation to use trains become obsolete. The result is the operation of independently powered GEFT cars in sequences. This transformation allows the use of tires rather than steel wheels which reduces noise and paves the way for GEFT cars to transfer back and forth from highways to railways. The primary benefit of railways, when available, includes operating above the speed limits of highways and accessing smoother surfaces that allow for both higher speeds and higher energy efficiencies. Designs are possible to operate GEFT at 200 mph on railway tracks which are otherwise limited to trains at less than 70 mph.

Methods

OpenFOAM CFD software was used to simulate digital prototypes from prepared STL files. Methods were matched to maintain fidelity and methods analogous to those within the field [20-22]. Two-dimensional (2D) simulations were used to identify trends in performance while three-dimensional (3D) simulations were performed on the final prototypes and key designs. 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 symmetrically presented with blue as low pressures, red as high pressures, and passing through green at 0-gauge pressure.

For ground effect simulations, the ground was simulated as a lower boundary condition with a velocity equal to the free stream air. Velocity profiles are from the reference frame of the airfoil/digital prototype. Propulsion sources are modelled as rectangular prisms. Free steam flow boundaries were simulated at a minimum of 10 chord lengths from the vehicle in free stream directions.

2D simulations are referred to as being performed on airfoils or wing sections. Some 2D simulations were performed with SimFlow software. 3D simulations are referred to as being performed on digital prototypes or GEM.

GEFT designs are the only GEM designs considered in this work, and all GEFT digital prototypes have vertical fences which are downward extensions of vertical sides. The height of GEFT are reported based on the horizontal part of the lower surface and do not include ducted fans, fences, or trailing flaps. A trailing section of lower surfaces with increased pitch is considered a flap. In the absence of further clarification the ratio of fence extension to GEFT height is approximately 0.3 and the ratio of flap extension to GEFT height is approximately 0.1.

OpenFoam simulation reports lift and drag coefficients based on the same reference value for area which may be different than the scale of anticipated GEFT vehicles. To a first approximation, within 1-2 orders of magnitude the simulations results are independent of scale and are typically performed at 40 m/s with a chord near 1 m in length.

The data reported in this work are C_D as calculated by OpenFoam with a planform reference area of $1m^2$. If the STL model's planform area is different than $1\ m^2$, the values from OpenFoam are divided by the actual planform area. L/D is calculated as the ratio of C_L to C_D.

Stability and Control

Mercedes cars spontaneously flew off the road in the 1999 the Le Mans races due to the reversal of pressure forces under the cars. Computational fluid dynamics (CFD) is able to simulate the spontaneous flight of those cars as well as design features which will operate along with steady and controlled lift generation in GEFT operation.

Figure 2 provides a digital prototype of a sportscar with pressure profiles for operation a -1°, 0°, 1° and 2° vehicle pitch. As illustrated by Figure 2, if a bump pushes the front of the car upward, a higher pressure develops at the trailing section of the lower surface leading to a drop at the front of the car until the front wheels balance the downward trend. In aerospace engineering, a common design feature is to ensure a vehicle's center of gravity is in front of the center of lift to prevent the car from flipping nose over tail. In steady-level cruising, the upward forces of the wheels balance the downward force of weight and lift.

A measure of the effectiveness of the GEFT design is the ratio of lift to drag forces, referred to as "L/D." Table 1 summarizes L/D and other parameters which characterize the performances of sportscars and GEFT. A negative L/D identifies aerodynamic suction, negative lift, pulling down on the vehicle to increase traction. As identified by Table 1, increasing the pitch of a sportscar can create the precarious condition where aerodynamic lift can cause the vehicle to take flight as pitch increases.

Table 1. Impact of pitch on efficiency and COL. The COL does not account for weight supported by wheels, and so, the aerodynamic center of lift may be in front of or behind the vehicle.

	Sportscar (Fig. 2)		**GEFT (S = 0) (Fig. 3)**		**GEFT (S = 5) (Fig. 4)**	
Pitch	L/D	COL	L/D	COL	L/D	COL
-1	-2.67	0.29*	1.68	1.56*	3.42	1.02
0	-0.44	0.71	12.92	0.602	18.33	0.574
2	2.84	0.58	6.96	0.706	7.74	0.723

The pressure profiles for the GEFT design are provided by Figure 3. At positive pitch, lower pressures on the front of the vehicle cause the car to automatically (i.e. passively) come to rest on the front wheels. The primary difference of the GEFT design is the lower cavity's trailing flap which generates higher pressures under the car causing aerodynamic lift which reduces weight on the wheels. Higher pressures which form at the trailing edge propagate forward at the speed of sound, reaching the leading edge when side fences sufficiently block the lateral loss of pressure.

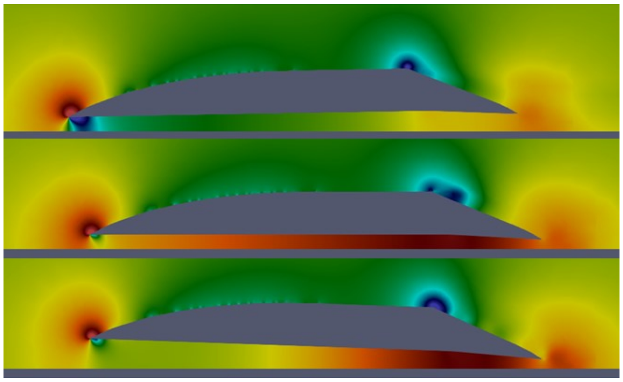

Figure 3. Illustration of GEFT midsection pressure profiles with ducted fan off.

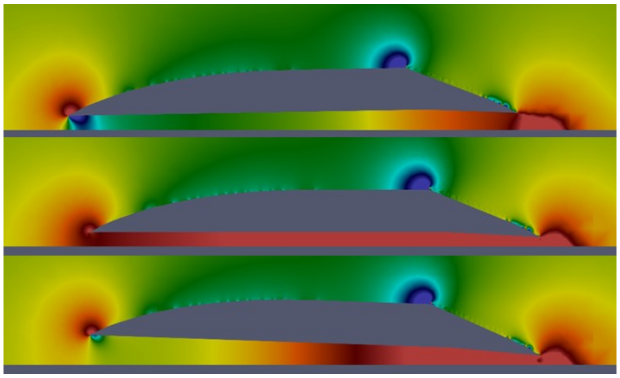

Figure 4. Illustration of GEFT midsection pressure profiles with ducted fan on.

A key aspect of the GEFT design is illustrated by comparing Figure 3 without a ducted fan to Figure 4 with the ducted fan on. The ducted fan forces more air along the trailing taper, where the air flow follows the taper eventually impacts the ground and creates a higher pressure at the trailing stagnation point. The higher pressure more robustly expands forward while the ducted fan increases the "pull" of air over the top of the car. The combination lowers the leading-edge stagnation point and leads to a higher lift pressure throughout the car's lower surface.

Transformation of Sportscar to GEFT

The primary feature that transforms an underbody from negative to positive lift for GEFT is the addition of a trailing flap. The cavity's flap both assists in high pressure creation and blocks the created pressure from dissipating rearward. The impact of the trailing flap is further exemplified by the series of pressure profiles of Figure 5. The addition of a trailing-edge flap to an otherwise flat underbody leads to an immediate increase in pressure.

High and continuous pressures below the underbody can be achieved by air flowing along a trailing taper which creates a trailing-edge stagnation point below and behind the trailing flap (right column of Figure 5); that pressure expands forward below the underbody. An alternative design with a flap of very low clearance, (bottom row of Figure 5), restricts the extent to which lower pressures behind the car are able to expand forward.

For a car one meter in height, the clearance ratio for the 100% flap of Figure 5 is two cm. Two cm is below the minimum clearance allowed in sportscar racing, which is about three cm. While it is practical to operate fences above a smooth railway track at a two cm clearance, it is less practical to operate a flap across the road or railway bed at this low clearance.

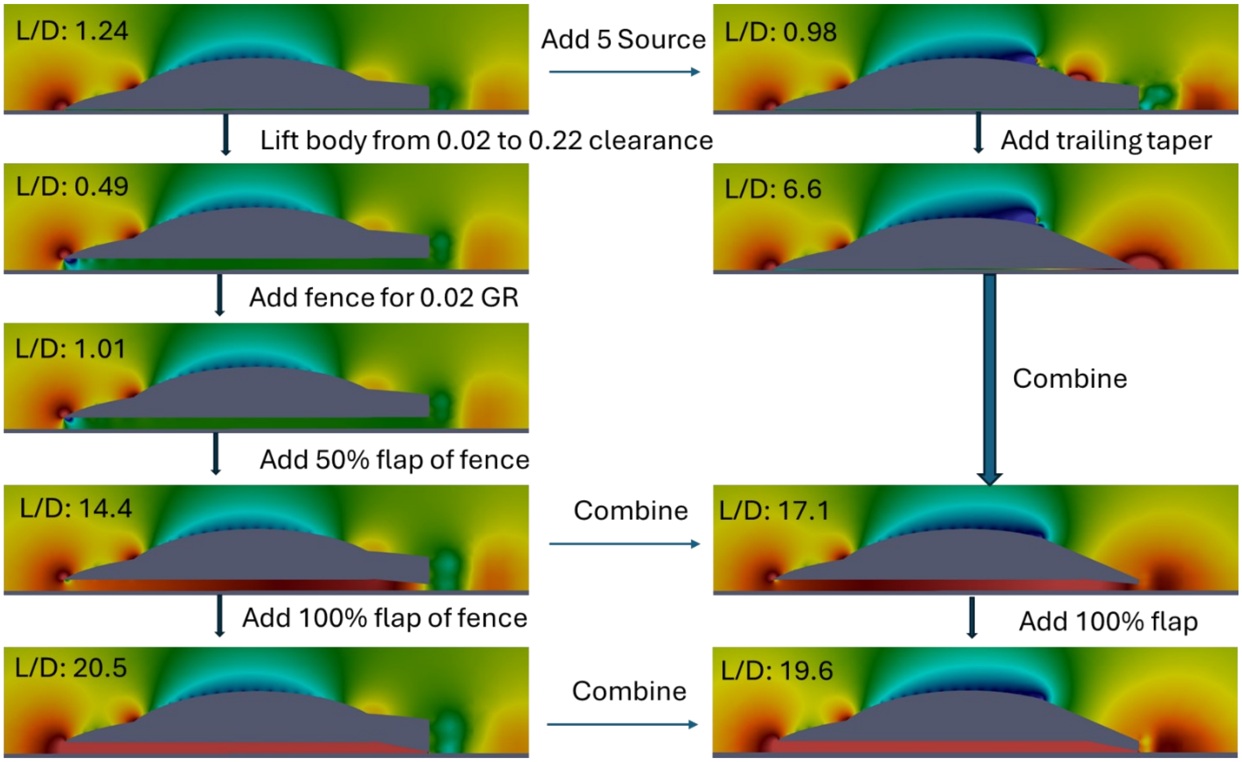

Figure 5. Impact of features that transform a sportscar to GEFT at an aspect ratio of 0.3. Left Path: Lower surface modifications. Right Path: Upper surface modifications.

Spoiler Versus Diffuser

A spoiler can create a downward force on the rear end of a vehicle [23-25]. Since the spoiler creates its own stagnation point with higher pressure, a spoiler increases drag. As an alternative, the back end can be placed farther off the ground to eliminate the drag created by the spoiler. However, when the back end of the undercarriage is raised, the pressure profile changes as the pitch is increased. When raised, a low pressure persists under the back end instead of a higher pressure, this can lead to the center of pressure moving forward. If the center of pressure proceeds forward past the center of gravity, the vehicle may flip upwards as occurred during the 1990's le mans races. For this reason, spoilers are regularly utilized to ensure maximum stability for race cars.

Impact of Center of Lift and Passive Stability

Gravity and lift forces may be represented as acting on a single point on the car with the respective names of center of gravity (CG) and center of lift (COL). Figure 6 illustrates example modes of operation. For the sportscar, a negative lift force pulls down on the vehicle and increases the traction of the tires, such as illustrated by Figure 6b were the COL acts to increase traction of the front wheels for turning.

For GEFT, the objective is to decrease rolling losses. Lift decreases the downward force on both front and rear wheels. A good mode of operation for GEFT is with some weight on wheels to maintain the fences at low clearances with the road or rails and enable regenerative braking. With lower weight on the wheels, the thrust and guidance need to be supplemented with ducted fans and ailerons.

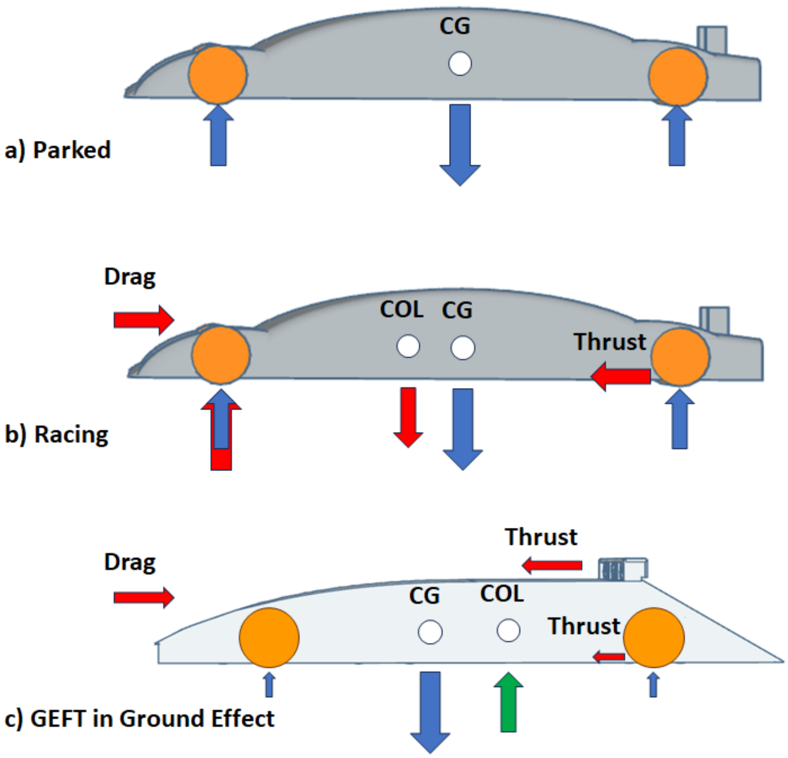

Figure 6. Impact of lift and center of lift (COL) on force balances of: a) parked sportscar, b) racing sportscar, and c) GEFT in ground effect flight.

A common design criterion for aircraft is to have the CG in front of the COL where the center of gravity is able to passively counter perturbations that drive the nose up or down. For cars with wheels, the CG passively adjusts for nose up perturbations causing and the wheels block the nose from being driven into the ground from those nose down perturbations.

For GEFT with wheels on the ground, the car aerodynamics passively adjust for nose-up perturbations while the wheels block nose-down perturbations preventing the nose from colliding with the ground. A typical approach in aircraft design is to have aerodynamics around the wings and body. In combination with a center of gravity in front of the center of lift, these passively adjust for a nose-up perturbation. For nose down perturbations, the smaller wings at the tail ("horizontal stabilizers") are able to passively nudge the aircraft back to the set point pitch which can be adjusted by flaps on wings or the horizontal stabilizers.

The B2 bomber is able to operate without a tail by using active control features which took time and more-evolved electronics to develop. This is part of the reason why cars took flight in many instances up until the 2000. The active control required for their stability remains a primary reason they maintain specialized use.

Table 1 summarizes example data on how the COL changes with pitch. The data of Table 1 agrees with the qualitative interpretations of the pressure profiles of Figures 2 through 6, with the figures providing greater insight into mechanics.

The best form of stability is passive stability where a perturbation in pitch. *Cl < 0.1 may cause greater errors in this value.

Spoilers, Diffusers, and The Speed of Sound

Air expands from high pressure to low pressure at the speed of sound. Once a pressure field forms, it will expand in all directions except as blocked by walls. Air under pressure will expand against oncoming air flow to change flows and pressures throughout the car surface; it will expand under and over the car's sides to reduce higher pressures and increase lower pressures.

Figure 7 illustrates how combinations of a front spoiler and a diffuser impact pressure profiles on a car. The Figure 7 simulation is of 2D slices, made under the condition of no sideways pressure expansion; therefore, the magnitude of the gauge pressures would be less for an actual car. The ground blocks downward expansion of air; this is why cars exhibit exceptional enhancements of traction or lift in ground effect. Fences extending below the sides of the vehicle allow the vehicle to approach the pressure profiles of the lower surface of Figure 7; however, fences are less effective on upper surfaces since pressures continue to dissipate upward.

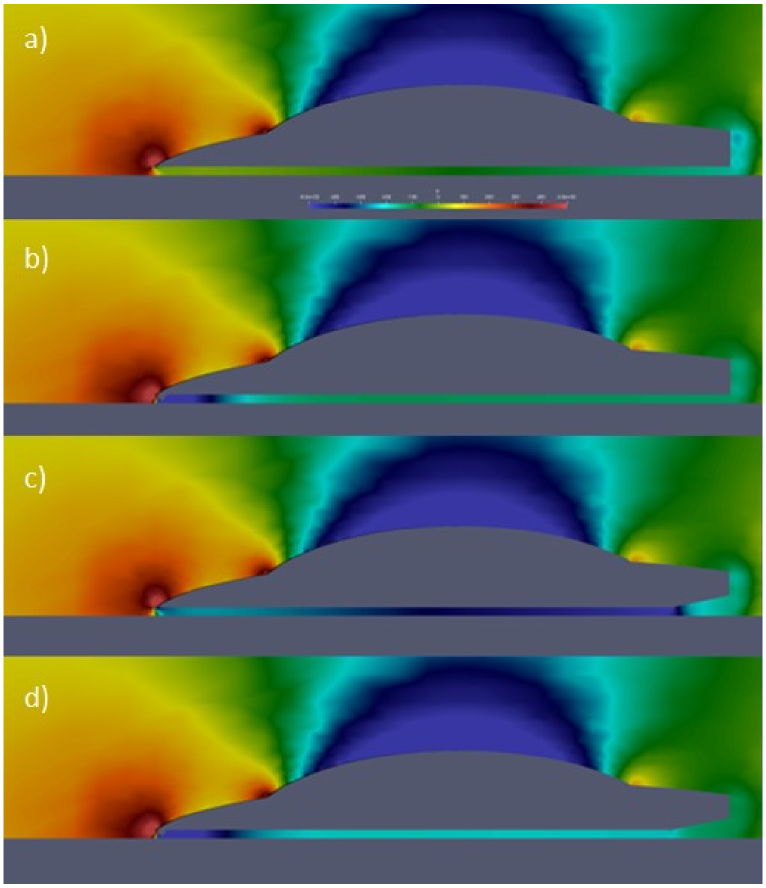

Figure 7. Impact of front spoiler and diffuser on pressure profiles in absence of dissipation of pressure across sides of car.

In the absence of a front spoiler, the pressure under a horizontal lower surface is close to the pressure of the surrounding air. With the addition of the front spoiler, the magnitude of the leading-edge stagnation point increases which impacts oncoming air, directing more over the car. Immediately behind the front spoiler, the lower air flow expands to fill the cavity, resulting in a lower pressure.

A diffuser without the front spoiler lowers the pressure throughout the lower surface, but with a smaller leading edge stagnation point. The combination of a front spoiler and diffuser is not as effective as a diffuser alone for the settings of these simulations. The similarities of the pressure profiles requires a more-sensitive analysis to identify improvements which are available with the lift and drag coefficients of Table 2.

Table 2. Lift and drag coefficients corresponding to Figures 7 and 8.

F-Spoil	Diffuser	Flap	L/D	Cd	Cd-Visc
n	y	n	-3.2	0.0044	0.00075
y	y	n	-0.2	0.0046	0.00055
y	n	n	2.0	0.0046	0.00055
y	n	0.5	3.3	0.0046	0.00054
n	n	n	4.8	0.0045	0.00074
n	n	0.5	8.1	0.0045	0.00070
y	n	y	12.0	0.0047	0.00050
n	n	y	19.5	0.0047	0.00055
n	y	y	20.9	0.0047	0.00053

Table 2 summarizes drag and lift performance data from least to greatest lift. Higher lift correlates with the flap, where the flap creates a higher pressure on its leading surface that extends forward through the lower surface. A flap extension of 67% (of lower body clearance) generated considerably more lift than a flap of 33%. Figure 8 summarizes pressure profiles with flaps where high lift is characterized by the higher pressure (red) extending along the entire undercarriage.

Suction (i.e., negative lift) was generated by only the diffuser absent the spoiler or flap and the front spoiler with a diffuser. The front spoiler without a diffuser generated lift where the lower pressure below the car was not enough to compensate for the lower pressure above the car.

When a flap creates a restriction to air flow at the rear of the underbody, significant amounts of lift can be generated as illustrated by L/D values near 20 in Table 2. For GEFT, fences block the sideways expansion of higher-pressure air from the cavity.

Table 3 summarizes the drag and lift performance data for 3D racecars. The table shows the impact of adding the cumulative features of a front spoiler, side fences, and diffuser at a 2% clearance. The features are analogous to Figure 7 with consistent trends as observed by the 2D experiments in the absence of sideways expansion of air.

Table 3. Lift and drag coefficients for 3D 0.3AR racecar with cumulative features.

Feature	L/D	Cd
0.3AR Racecar without spoiler	1.24 (-0.44 with spoiler)	0.023
Front Spoiler	0.49	0.026
Plus Side Fences	0.59	0.026
Plus a Rear Diffuser	-2.62	0.027

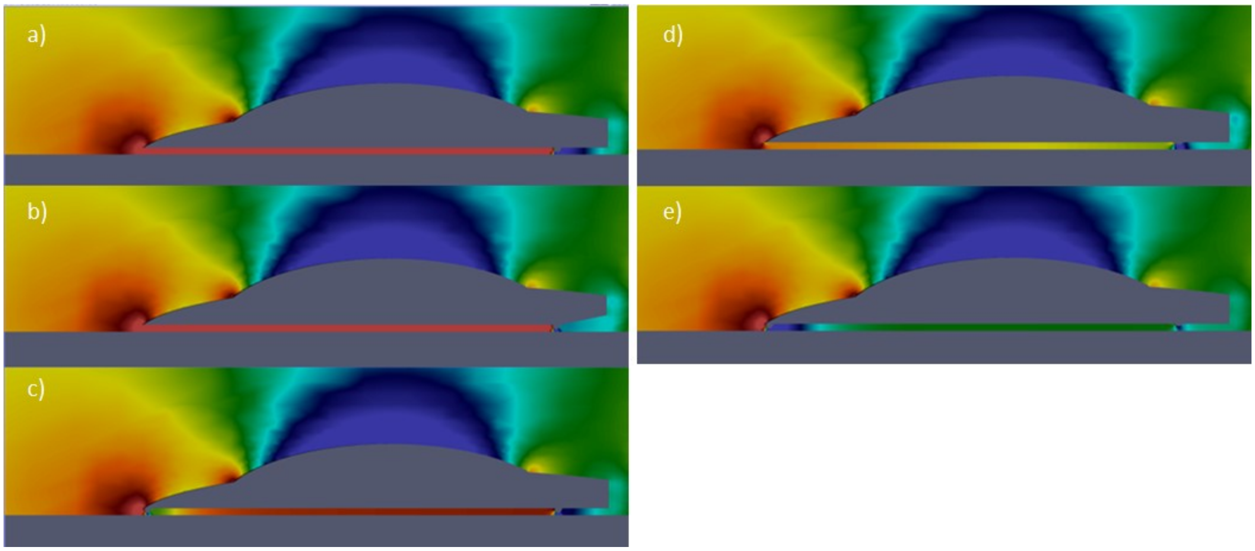

Figure 8. Impact of rear section flap on pressure profiles in absence of dissipation of pressure across sides of car.

Table 4 summarizes the impact of impact of vehicle pitch on vehicle lift (i.e. the L/D). While the combination of the front spoiler and diffuser creates the greatest suction, the front section without a spoiler leads to the greatest change in lift as a function of vehicle pitch. A rapid change from negative to positive pitch can cause the lift to change from suction to significant lift. This change in pitch can happen when a vehicle goes over a bump or hill crest. The greater the distance between the leading edge and wheels, the greater the change in clearance of the front spoiler and respective increase in lift. As such, mere bump in the road can send poorly designed race cars flying into the air.

Table 4. Impact of vehicle pitch on lift of car with front spoiler for 2D simulations.

Pitch	S	D	Flap	L/D	Cd
1	y	y	n	14.03	0.0043
0	y	y	n	-0.22	0.0046
-1	y	y	n	-1.02	0.0053
1	y	n	n	25.66	0.0044
0	y	n	n	1.97	0.0046
-1	y	n	n	-0.45	0.0052

The effective clearance of the front spoiler can impact how lift changes with spoiler clearance. The term "effective" is used with clearance since a grid or gap built into the spoiler allows additional air through to the lower cavity. Since the air flow through a grid is not significantly dependent on clearance, it creates stability against large and rapid changes in lift.

Traditional simple explanations of how air flow transforms into aerodynamic lift do not explain the trends in performance of Figures 7 and 8 and Tables 2 and 4. However, recognizing that air flow creates aerodynamic lift by processes of 1) creating higher pressures, 2) creating lower pressures, and 3) expansion of pressure at the speed of sound does explain observations.

Figure 9 highlights the pressure profiles of a car with diffuser at different pitches. Diffusers are able to increase traction forces with negative lift similar to a rear spoiler but without the added drag. Diffusers are a key component of race cars which improves generation of negative lift and maintains a sufficiently aerodynamic form to decrease drag for increased efficiency. In their basic form, they are simply an increase in clearance near the end of the vehicle, however, they frequently maintain strakes, fences, and increasing complex structures; the primary purpose of the is to reduce the sideways dissipation of lower pressures formed by the diffuser's progressively increasing cross-sectional area [26-28].

The last pressure profile of Figure 9 illustrates variations in pitch which show how the diffuser maintains lower pressure under the vehicle, particularly at the rear. This increases the overall negative lift on the vehicle, but does not completely prevent the buildup of high pressure under the front of the vehicle.

The car can spontaneously take flight when higher pressures under the car combine with the lower pressures above the car. Depending on the center of lift (COL) relative to the center of gravity, the flight may lead to the vehicle flipping nose over tail.

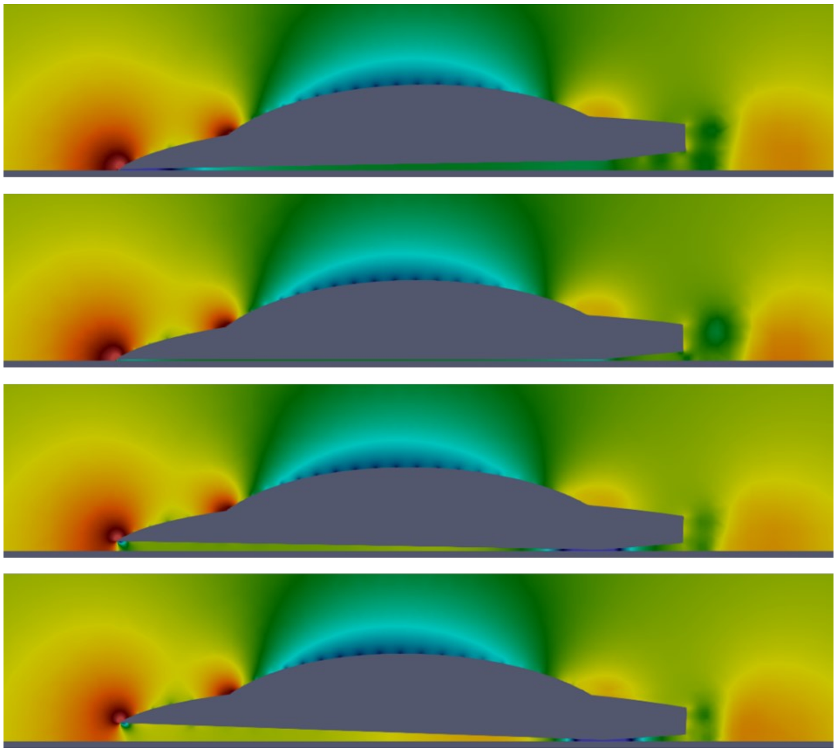

Figure 9. Impact of lower compartment trailing section diffuser on pressure profiles at pitches of -1, 0, 1, and 2 degrees with no underside fence.

Airfoil Comparison

While rarely mentioned in discussions of aerodynamics, the rapid expansion of air from higher to lower pressures has a dominating impact on pressure profiles and respective lift or downward suction. This is illustrated by the simple airfoil sections of Figure 10.

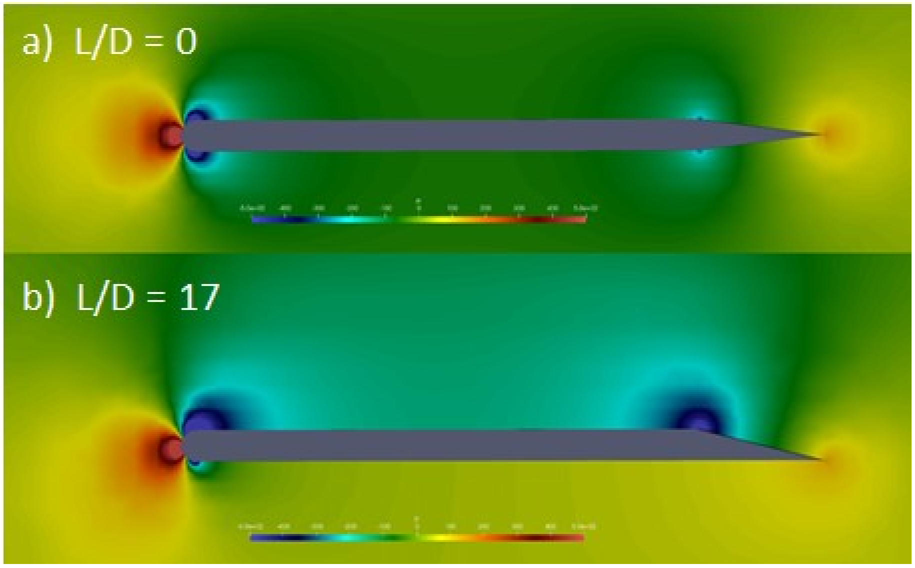

Figure 10. Illustrative example of how a change is shape at a trailing edge impacts the pressure profile throughout an object due to pressure propagating at the speed of sound.

Both airfoils have leading edge and trailing edge stagnation points. The higher pressures of the leading-edge stagnation points are initially formed due to the air flow impacting the leading edge, but when the pressure field is fully developed, the leading-edge higher pressures are sustained by air flow impacting and mixing with the pressure field with little velocity flow actually reaching the surface [29]. The higher pressures of the trailing-edge stagnation points are due to the collision and impacting of the upper surface air flow with the lower surface air flow.

Lower pressures form when the flow along the surface diverges from the curve of the surface. The curvature causing the low pressures is at the rounded-leading section and the sharp change in slope at the trailing tapers.

The base case airfoil of 10a is vertically symmetric, and so pressure forces on upper surfaces cancel pressure forces on lower surfaces to provide zero lift.

When the trailing taper is made steeper, a lower pressure forms on the upper surface. When the trailing-edge stagnation point is even with the lower surface, the higher pressures are able to freely expand forward along the underbody. The combination of unobstructed forward expansion of pressure on the bottom and unobstructed suction of the upper-surface trailing stagnation point changes the overall pressure profile. Higher pressures form on the lower surface and lower pressures form on the upper surface. Since the pressure expands at the speed of sound, it is able to expand against oncoming air flow. The forces are so strong that the leading-edge stagnation point migrates towards the lower surface.

These same forces clarify the changes in the pressure profiles of Figure 7, except for the onset of turbulence. The sportscar pressure profiles do not have trailing-edge stagnation points because large differences in pressure cause turbulent mixing. The GEFT of Figures 3 and 4 have trailing-section stagnation points since the continuous taper causes more-gradual changes in pressure and avoids of turbulent mixing.

The mixing of turbulence results in the rapid degradation of energy preserved within the pressure gradients. GEFT are designed to generate aerodynamic lift and to operate at higher efficiencies. The higher efficiencies are possible due to the absence of turbulent mixing.

For the 2D simulations of Figure 7, the lower pressure below the underbody is preserved until it reaches the trailing car's trailing edge; the result is a very high suction that pulls in air which expands throughout the trailing half the car as further illustrated by Figure 10. The expansion of air forward decreases the effectiveness of the spoiler. When a diffuser or negative pitch is added, the progressively increasing cross-sectional area of the lower cavity more-effectively compensates for the expansion of trailing pressures below the undercarriage.

A Misguided Aerospace Industry

A number of terms are frequently used to explain lift forces in the aerospace industry, including: venturi effect, vortices, Bernoulli theory of lift, turning air theory of lift, momentum theory of lift, and ram effect. In a similar disposition; sportscars, aircraft, and hovercraft are isolated in discussion and explanation. Those terms and explanations are preponderance of errors in insight and explanation.

Air expands at the speed of sound, which is understood at the molecular level and accepted at the practical application. The concept is incorporated into the underlying equations in fluid dynamics, including CFD programming (i.e., the Navier-Stokes equations). However, through the decades, the expansion of air at the speed of sound has not been commonly included in simple explanations of aerodynamic lift.

The fundamentally accurate explanation of how air flow crates lift forces is based on three basic concepts of physics:

1. Impacting air flows create higher pressures; this includes the impact of air flows with surfaces, with pressure fields, and with other air flows.
2. Diverging air flow create lower pressures; this includes air flowing over a curved surface such as that of the upper surface of a wing.
3. Higher pressure air expands towards lower pressure air at the speed of sound, except as blocked by surfaces.

These three basic concepts apply to sportscars, aircraft, hovercraft, and GEFT.

Venturi effect explanations are especially in error. Figure 11 provides an expanded view of the flap on a sportscar. The Venturi effect explains velocity and pressure as the simple tradeoff between pressure and velocity where increasing velocity through a restriction leads to decreasing pressure. The venturi effect would lead to similar higher pressures immediately before and after the flap of Figure 11. The actual behavior leading to the pressure profile of Figure 11 includes: 1) impacting air leads to higher pressures being generated in front of the flap, 2) the pressure forces propagate to the front of the vehicle cause air flow to be diverted over the vehicle with decreasing air flow under the vehicle, 3) the decreased air flow after the flap leads to lower pressures behind the flap, and 4) lower pressures at the rear of the vehicle cause even lower pressures immediately behind the flap. The “venturi effect” is in error qualitatively and quantitatively in open air systems.

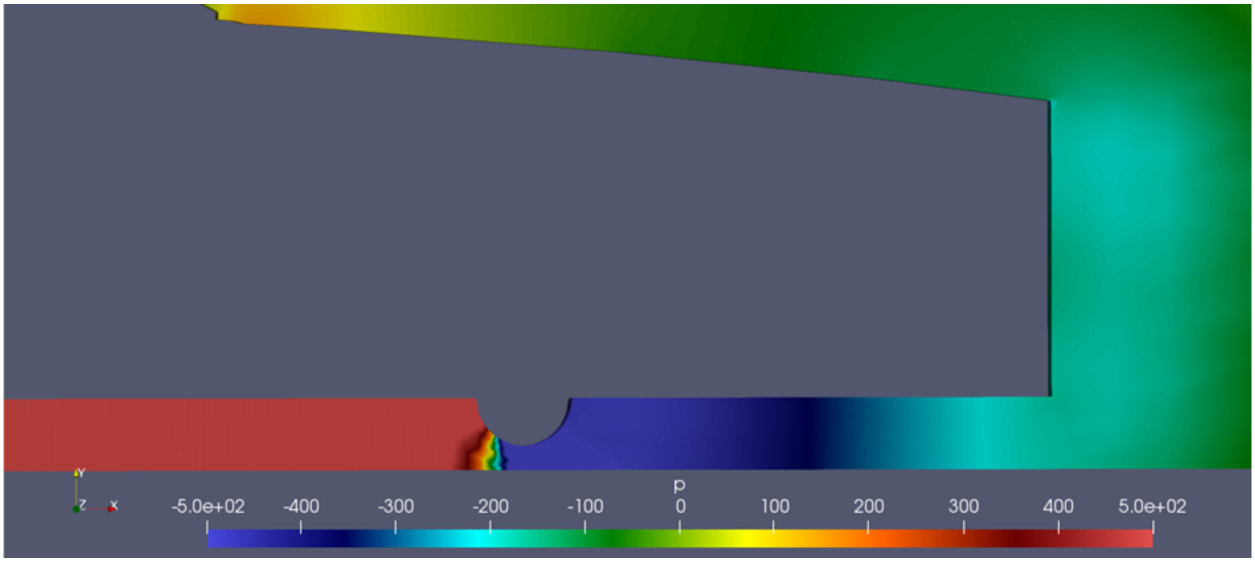

Figure 11. Expanded view of Figure 8c sportscar with flap. The pressure scale is in m^2/s^2, with a converted pressure scale going from about -0.1 to 0.1 psig.

The "Bernoulli theory of lift" and "turning air theory of lift" are erroneous because they are simply correlations of how pressure changes with changes in velocity [17]. To design an aircraft based on these erroneous theories is like trying to fix a gasoline engine without understanding how compression of air in cylinders is critical for the engine to work. Correlations have been used to develop erroneous analogies to explain how pressures form on cars and airplanes for decades.

A more detailed discussion of these concepts and their use to create heuristics for designing vehicles is beyond the scope of this paper. However, they do describe the formation of most of the highly complex pressure profile fields summarized within this article. The low-pressure formations behind the non-tapered trailing edges of the sportscar's pressure profiles are due to turbulence. Turbulence is the result of airstream mixing which would substantiate a fourth concept more complex than 1-3 above.

Energy Efficiency

GEFT attain substantially improved energy efficiency by elimination of most rolling losses and achieving lower aerodynamic drag resistance than other vehicles. For highway cruising, the rolling loss of a fully loaded tractor trailer is about equal to aerodynamic losses, and the replacing of 95% of the wheel suspension with aerodynamic suspension substantially eliminates these rolling losses.

Lower levels of aerodynamic drag are attained through two transformations. First, the ducted fan and trailing taper transform the lower pressure area at the rear of the sportscar to a pressure averaging at near-zero gauge pressure; this eliminates the drag caused by the low pressure on the back surfaces of the racecar. Secondly, versus the sportscar, GEFT has a single higher-pressure area at the front of the vehicle; this is due to a deflecting surface having a continuously increasing (less negative) pitch.

Figure 12 compares the pressure profiles, L/D, and drag coefficients of the sportscar, GEFT, and GEFT with the ducted fan on. The drag coefficient of GEFT with the ducted fan on is about half that of the sportscar. The low drag coefficient of GEFT with the ducted fan on is due to lower pressures on the front section that induce thrust on the vehicle.

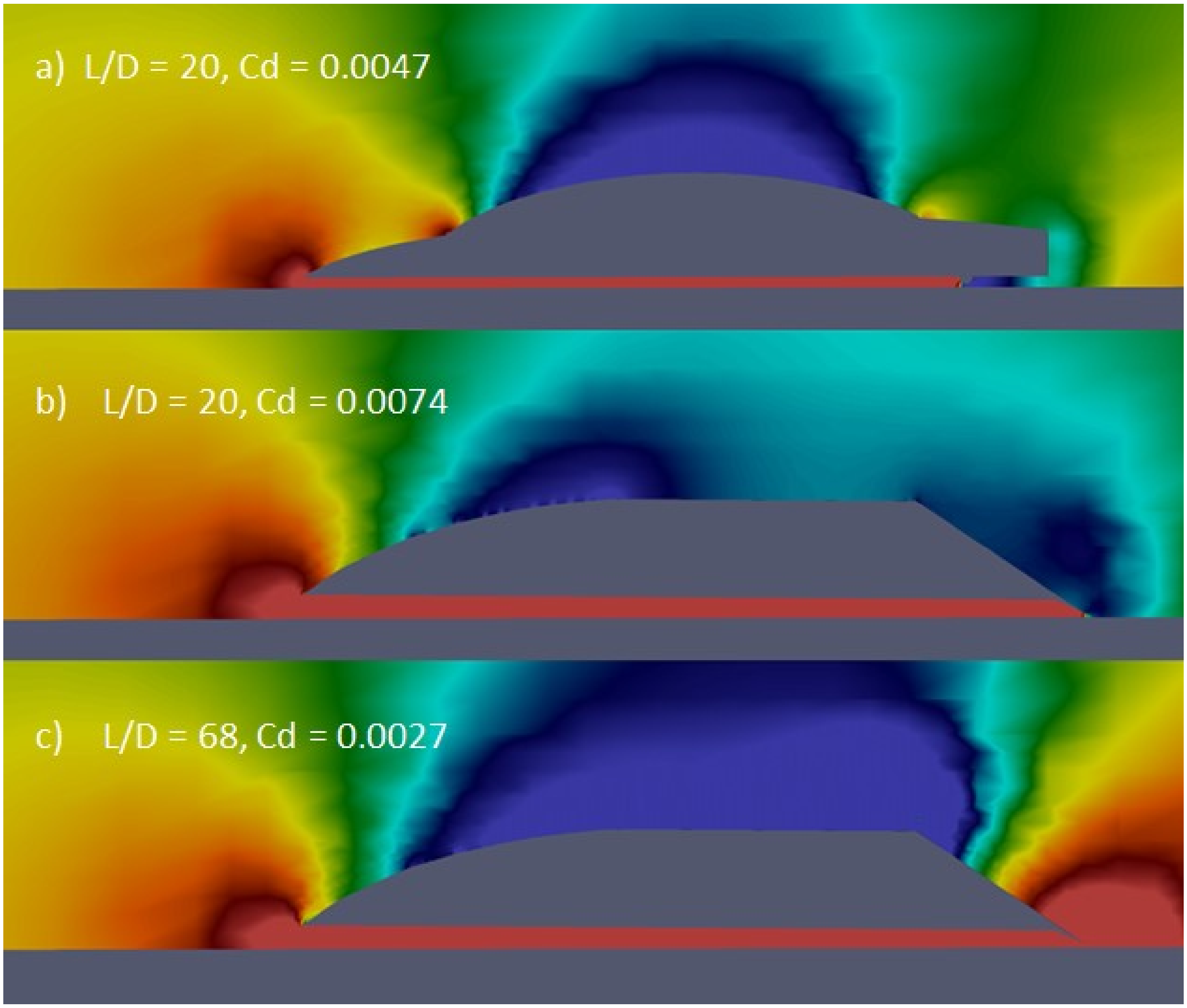

Figure 12. 2D Pressure profile comparison of sportscar, GEFT, and GEFT with ducted fan on.

Railway Transit

The U.S. has fallen behind other countries in highspeed trains, maglev, and hyperloop development. China and Japan have emerged as world leaders on maglev technologies with operational commercial lines. High speed trains typically weight 300 to 500 tons, requiring expensive, robust tracks with gradual turns to handle travel at 200 mph. Maglev trains may weigh less but require continuous and expensive new tracks [30-32].

GEFT is able to achieve high speeds on existing tracks throughout the world by traveling on a cushion of air with minimal weight on rubber tires. Example weights of GEFT are 150 lbs. per ft of length. At 85 mph, this weight translates to three tons for a 40 ft railcar supporting about 20 passengers. Both suspension and turning are be based primarily on aerodynamics acting on the body, flaps, and ailerons—not on the rails. Railway track infrastructure is available between and throughout all major cities. This is particularly useful for the U.S. as the expansive distance between cities is exponentially more expensive for the implementation of high-speed rail and maglev tracks and their maintenance, while these technologies all for the use of already developed infrastructure at greater efficiency.

At 170 mph, the capacity is 600 lbs. per ft. The maximum weight of aerodynamic lift increases with velocity squared.

The energy efficiency becomes better than all alternatives.

The greatest advantage goes beyond what has even been considered for highspeed trains and maglev. GEFT are able to travel in close proximity as train units where the trailing cars stop at stations while the rest of the train cars continues [14]. In the same manner, stopped GEFT cars can depart stations ahead of an incoming train to dynamically form the train's lead positions. This approach is illustrated by Figure 13.

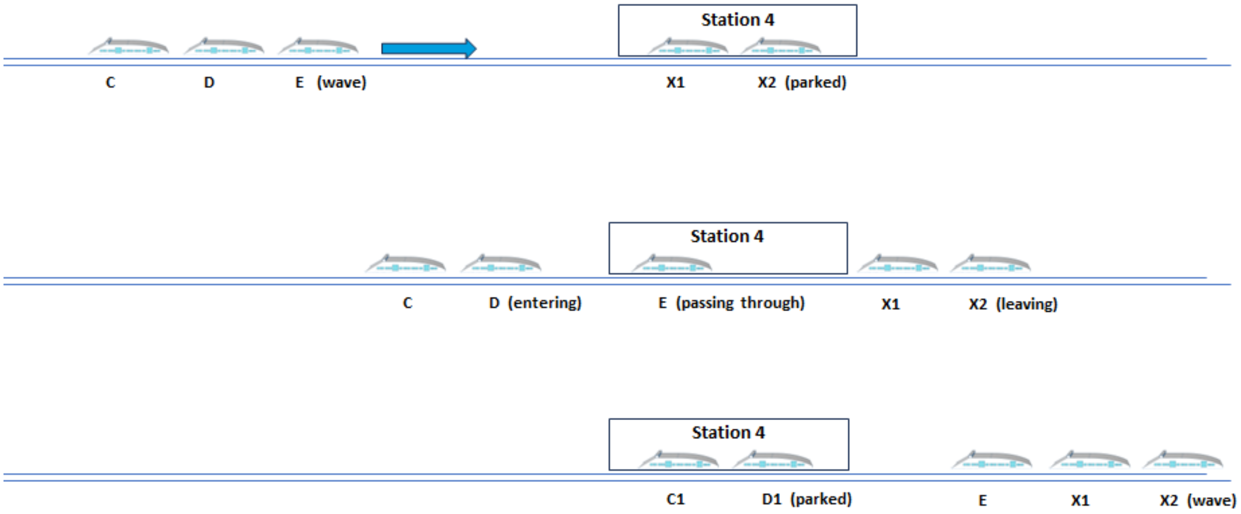

Figure 13. Illustration of operation of stations where cars parked at stations take lead positions in dynamic trains while trailing cars of the train stop at the stations.

Operation is compatible with freight and capacity by using initiating "dynamic waves of trains" with trailing cars stopping at stations. Tires would allow cars to turn around at locations without rails that would otherwise accommodate reversal of direction; this strategy would allow the transit capacity to be varied along a railway track to improve service and better use car passenger capacities.

By changing the length of the dynamic trains, the number of stations a car bypasses between stops is modified, which enables nonstop service between each pair of stations on a line. Operating the GEFT nonstop at speeds 2X to 3X the speeds of contemporary trains would cut transit times and costs by more than half. When applied on a global basis, the annual value is multiple trillion dollars per year from the saved money value of time. The value is greater if the rail system replaces car costs, including parking and insurance costs.

The multi-trillion-dollar annual impact is based only on commuter transit applications. Intercity transit can displace air transit without the delays and costs of going through airports, yet providing similar transit speeds. Freight and parcel transit can be mixed in with passenger transit for larger markets to replace some trucking and the related diesel fuel consumption. The capabilities continue to expand with rail/road/water multimodality.

The GEFT advancements are, in part, due to an improved understanding of aerodynamics. That same improved understanding enables hyperloop corridors for cars where entrances and exits are operated as open doors with Bernoulli loops reducing pressure of the air around the vehicle as it enters the tunnels. This is critically important because it allows hyperloop transit to be achieved with incremental changes to existing rail routes and as part of nonstop service where effective travel velocities are faster than airliners. The tunnels can operate with perpetual tailwinds in both directions to compete with airliner speeds.

Minor variations of the design features in common use at sportscar raceways make these incredible advances possible.

Lift Forces

Simulations of GEFT identify that the lift forces are primarily on the lower surface at pressures approaching air's dynamic pressure. Table 5 summarizes values of air's dynamic pressure, which is a function of the speed of the car relative to oncoming air.

Table 5. Air's dynamic pressure at density of 1.25 kg/m^3, car width of 8.5 ft. The power depends on the L/D efficiencies which is set at 20 for a 6' high truck at an aspect ratio of 0.2.

U (m/s)	U mph	Pa kg/m/s^2	Load lb/ft	Power W/m^2
20	45	248	44	248
30	67	563	100	845
40	90	1000	178	2000
50	112	1563	277	3910

At lower velocities, more of the weight rests on the tires. The L/D is not a strong function of velocity, and so, the power needs are proportional to velocity. For sunny days, solar power can be collected at about 250 W/m^2, which means that direct solar power can fully sustain travel at 45 mph. Batteries can be charged when parked or at charge stations to sustain higher speeds. Higher speeds are possible with increases in surface area for solar power, higher aspect ratio vehicles, and with improving photovoltaic cells. Optimal vehicle designs would reduce battery weights and costs for car bodies fully covered with solar cells. Direct solar cars and trucks are viable in the near term at the 60-70 mph for ultra-light GEFT designs at conditions leading to L/D in excess of 30, with modest advances in photovoltaic cell efficiency, and with use of photovoltaic cells on upper and side surfaces.

While direct solar powering of trains traveling at 200 mph is not in the near future, GEFT technology is positioned to replace most petroleum fuel use for transit via a combination of solar power on vehicles and national grid electricity from a range of sources. Solar powered cars and tow-assist trailers are attainable in the near term with the ability to provide power to buildings from idle solar vehicles.

Concluding Thoughts

GEFT has the ability to revolutionize transit by cutting transit times and costs in half; it is also able to substantially convert the transit industry's high dependence on diesel and aviation fuels to clean solar power and grid electricity. Critical design features include:

- A lower cavity fence that would travel in close clearances to a rail or highway to block the dispersion of lift pressures, clearances range from a half inch to two inches.
- A design that uses an upper surface trailing section ducted fan to reduce drag and form the trailing-edge lower-surface stagnation point at shorter vehicle lengths as critical to attain the highest efficiencies.

Sportscar racing routinely uses low vehicle-road clearances. Railway tracks will more easily sustain low clearance travel particularly for GEFT where the clearance is determined by wheels and side fences. The ducted fan configurations open the doorway for a technological revolution.

References

[1] Suppes, A.B., and Suppes, G., "Thin Cambered Lifting Bodies in Ground Effect Flight," *Engrxix Engineering Archive Pre-Print,* No. 1, 2024, https://doi.org/10.31224/4136

[2] Katz, J., "Aerodynamics of Race Cars," *Annual Review of Fluid Mechanics,* Vol. 38, No. Volume 38, 2006, 2006, pp. 27–63. 10.1146/annurev.fluid.38.050304.092016

[3] Zhang, Z., Wang, Q., Song, S., Zhang, C., Ren, L., and Zhang, Y., "Joint Research on Aerodynamic Characteristics and Handling Stability of Racing Car under Different Body Attitudes," *Energies,* Vol. 15, No. 1, 2022, pp. 393. 10.3390/en15010393

[4] Zhang, X., Toet, W., and Zerihan, J., "Ground Effect Aerodynamics of Race Cars," *Applied Mechanics Reviews,* Vol. 59, No. 1, 2006, pp. 33–49. 10.1115/1.2110263

[5] Braghin, F., Marchetta, F., and Sabbioni, E., "A Traction and Instability Control Logic for Formula Student Race Cars," American Society of Mechanical Engineers Digital Collection, 2008/09/05, pp. 279–286. 10.1115/ESDA2006-95553

[6] Ma, X., Li, J., Zhao, J., and Chen, J., "Aerodynamic characteristics of the race car in pitch and roll attitude," *International Journal of Numerical Methods for Heat & Fluid Flow,* Vol. 35, 2024, pp. 330–357. 10.1108/HFF-05-2024-0375

[7] Suppes, G., and Suppes, A., "Ground Effect Flight Transit (GEFT) – Approaches to Design," Cambridge University Press, Cambridge Open Engage, 2024. https://www.cambridge.org/engage/coe/article-details/66b2340b01103d79c5e7ab2310.33774/coe-2024-2c87q

[8] Suppes, A., and Suppes, G., "New Benchmarks in Ground-Effect Flight Energy Efficiency," July 102024https://www.researchsquare.com/article/rs-4707178/v1https://doi.org/10.21203/rs.3.rs-4707178/v1 [cited Jul 29 2024].

[9] Suppes, A., and Suppes, G., "Seamless Multimodal Passenger-Oriented Service for River and Bay Communities," *TechRxiv Preprints,* 2025, https://doi.org/10.36227/techrxiv.173932982.23714576/v1

[10] Suppes, A., and Suppes, G., "Extreme Multimodality and Seamless Transit," *TechRxiv Preprints,* 2025, https://doi.org/10.36227/techrxiv.173932968.82108672/v1

[11] Suppes, A., and Suppes, G., "Ground Effect Flight Transit (GEFT) – Towards Trans-Modal Sustainability," Vol. 1, 2024, https://doi.org/10.33774/coe-2024-prxvr

[12] Suppes, G., and Suppes, A., "Ground Effect Flight Transit (GEFT) in Subways," Vol. 1, 2024, https://doi.org/10.33774/coe-2024-6w0lw

[13] Staff, M.C.S., "DC to Baltimore in 15 Minutes As Plans For High-Speed Train Move Forward," [online database]-02-082025https://mocoshow.com/2025/02/08/dc-to-baltimore-in-15-minutes-as-plans-for-high-speed-train-move-forward/ [cited Mar 3 2025].

[14] Suppes, A., and Suppes, G., "GEFT Scheduling to Maximize Value of Current Infrastructure and Upside Potential," *Cambridge Open Engage [Pre-Print],* 2025, https://doi.org/10.33774/coe-2025-x07tg

[15] Suppes, A., Suppes, G., and Al-Moameri, H., "Overcoming Boundary-Layer Separation with Distributed Propulsion," *Sustainable Engineering and Technological Sciences,* Vol. 1, No. 01, 2025, pp. 71–89. 10.70516/7a9e2y30

[16] Suppes, G., and Suppes, A., "Critical Data and Thinking in Ground Effect Vehicle Design," Cambridge University Press, Cambridge Open Engage, 2024. https://www.cambridge.org/engage/https://doi.org/10.33774/coe-2024-76mzx

[17] Suppes, A., Suppes, G., Lubguban, A., and Al-Maomeri, H., "An Airfoil Science Including Causality," *Cambridge Engage,* 2024, 10.33774/coe-2024-w4qtp

[18] Suppes, A., Suppes, G., Lubguban, A.A., and Al-Moameri, H.H., "Kinetic theory of gases: explanation of aerodynamic lift," *Aviation (in Review),* 2024,

[19] L. L. Bashford, S. Al-Hamed, and C. Jenane, "Effects of Tire Size and Inflation Pressure on Tractive Performance," *Applied Engineering in Agriculture,* Vol. 9, No. 4, 1993, pp. 343–348.

[20] Klose, B., Spedding, G., and Jacobs, G., "Direct numerical simulation of cambered airfoil aerodynamics at Re = 20,000," 2021, https://doi.org/10.48550/arXiv.2108.04910

[21] Michna, J., and Rogowski, K., "Numerical Study of the Effect of the Reynolds Number and the Turbulence Intensity on the Performance of the NACA 0018 Airfoil at the Low Reynolds Number Regime," *Processes,* Vol. 10, 2022, pp. 1004. 10.3390/pr10051004

[22] Lee, D., Nonomura, T., Oyama, A., and Fujii, K., "Comparison of Numerical Methods Evaluating Airfoil Aerodynamic Characteristics at Low Reynolds Number," *Journal of Aircraft,* Vol. 52, 2015, pp. 296–306. 10.2514/1.C032721

[23] Iftekhar, A.K., "RACING THROUGH THE WIND: DECIPHERING THE AERODYNAMIC IMPACT OF SPOILER SHAPE AND SETTING ANGLES ON CAR PERFORMANCE," *International Journal of Advance Scientific Research,* Vol. 4, No. 01, 2024, pp. 1. 10.37547/ijasr-04-01-01

[24] Roslan, M.H., Hasbullah, H.H., Ramesh, T., Didane, D.H., Manshoor, B., and Kabrein, H.A., "Effect of a Spoiler on the Aerodynamic Performance of a Race Car on Track Using Two Different Turbulence Models," *Journal of Design for Sustainable and Environment,* Vol. 5, No. 2, 2023, pp. 28–37.

[25] H. Ragheb, and M. El-Gindy, "Rear wing spoiler effects on vehicle stability and aerodynamic performance | International Journal of Vehicle Systems Modelling and Testing," *International Journal of Vehicle Systems and Modelling and Testing,* Vol. 15, No. 4, 2022, pp. 289–307. https://doi.org/10.1504/IJVSMT.2021.122817

[26] Hassaan, M., Dewivedi, S., Khurshid, H., "Computational Study on the Diffuser of Formula Racing Car," Springer Nature, Singapore, 2023, pp. 481–496. 10.1007/978-981-99-1894-2_41

[27] Porcar Galán, L., "Study of the functioning and importance of diffusers in Formula 1 cars," 2020, https://upcommons.upc.edu/handle/2117/331430

[28] Ehirim, O., "Optimal Diffuser Design for Formula SAE Race Car Using an Innovative Geometry Buildup and CFD Simulation Setup with On-Track Testing Correlation," Warrendale, PA, 2012. https://www.sae.org/publications/technical-papers/content/2012-01-1169/

[29] Suppes, G., and Suppes, A., "Computational Analysis of Towed Solar Platform Aircraft," *Research Square,* 2023, pp. 1–29. https://doi.org/10.21203/rs.3.rs-4670250/v2

[30] Shibani, W.M., Zulkafli, M.F., and Basuno, B., "Methods of Transport Technologies: A Review On Using Tube/Tunnel Systems," *IOP Conference Series: Materials Science and Engineering,* Vol. 160, No. 1, 2016, pp. 012042. 10.1088/1757-899X/160/1/012042

[31] Noland, J.K., "Prospects and Challenges of the Hyperloop Transportation System: A Systematic Technology Review," *IEEE Access,* Vol. 9, No. 2021, pp. 28439–28458. 10.1109/ACCESS.2021.3057788

[32] Yaghoubi, H., Barazi, N., Kahkeshan, K., Zare, A., and Ghazanfari, H., "Technical Comparison of Maglev and Rail Rapid Transit Systems," *The 21st International Conference on Magnetically Levitated Systems and Linear Drives,* 2011, pp. 5.