WHEN THE WHOLE IS LESS THAN THE SUM OF ITS PARTS

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Abstract

"Hybrid-lift" vehicle concepts are those in which two or more primary lift elements (dynamic, static, or powered) are combined, with each element carrying a major fraction of the total lift, not merely trim, stabilizing, or control forces. In connection with a number of recent vehicle concepts, it has been conjectured that hybrid-lift vehicles derive economic or performance benefits from the concurrent use of different types of primary lift, in effect combining the advantages of each. Unfortunately, except for certain specialized missions, it is far easier to defend the contrary assertion: hybrid-lift vehicles are inherently non-optimal for line-haul vehicles, and tend to combine the *disadvantages* of all lift sources.

I. THE CHALLENGE

Please permit us to begin our paper with a dramatic challenge. This challenge is not intended to offend, but is instead offered as an unequivocally clear statement of our hypothesis:

THE ONE-LIFT OBSERVATION:

- Show me a vehicle that makes money reliably in line-haul, and I'll show you a non-hybrid.
- Show me a hybrid that looks better than its "competitor" concepts and I'll show you straw-men competitors.

II. MISSIONS AND SPEEDS

Much of the recent interest in high-speed marine vehicles has been motivated by potential applications in line-haul transportation, that is, carrying passengers or cargo over a more or less fixed stage length. At the end of the spectrum typified by relatively short stage lengths, it is by no means unusual for passenger and even passenger/automobile/truck ferries to operate in the 45-50 knot regime. For trans-oceanic stage lengths, commercial container carriers and military sealift ships operating in this speed regime are now contemplated, with the expectation of economic viability -- or at least military utility -- in spite of high unit fuel costs compared with conventional ships 20 knots slower.

This has not always been the case. Not so long ago, very high speeds were considered the province of combatants – destroyers and patrol craft of various types. Reasons for the change may be found in various areas: economic, geopolitical, and technological. At the risk (nay, the certainty) of oversimplification, it seems possible that future commercial or strategic sealift "ships" with useful payloads in the thousands of tons, will be designed to transit at unprecedented sea speeds, say, in the 50 knot regime or even higher; while future surface combatants may be designed as much for sensitive characteristics (such as low signatures) at "tactical" speeds significantly lower than that of present destroyers. The nature of missions in general, and the role of speed in particular, has changed dramatically even within the last ten years. It is still changing.

Nonetheless, it is important to keep one thing in mind. Many military missions (especially combat missions) involve deliberate and sustained operation *in more than one speed regime*. Even in civilian life, oceanographic research often imposes two or more speed regimes of importance, as does commercial fishing. By contrast, however, line-haul transit, whether for profit or for sealift, is supposed to be conducted at (or as close as possible to) *one economical speed*. This speed may or may not always be the original *design speed* of the ship, as the fuel price dislocations of the past have shown us well enough, but the point is that line-haul is basically a one-speed mission, barring special geographic constraints, such as wash restrictions, or environmental *force majeure*.

Two-speed missions may be viewed as one of the facts of life that drive designers of advanced marine vehicles, in their despair, to consider hybrid sources of lift. For example, an ASW or in stride mine warfare mission might require sprint (foil-borne, cushion-borne, or on-plane, as the case might be), and search (hull-borne, off-cushion, or off-plane). In some cases the practical difficulties of applying hybrid lift are so severe that a two-vehicle system emerges as a better choice for a two-speed mission.

By contrast, *if* a mission is truly a one-speed mission, which is what line-haul transit should be, then arguments for and against hybrid lift vehicles *should* be simpler. But they aren't.

III. SPEED AND LIFT

In the following discussion, the word "lift" is used not in the aerodynamic sense, but the economic one: "lift" is the force that opposes weight. For vehicles as a general concept, lift may be generated in various ways. For the vehicles of concern here, however, lift is generated entirely by pressures in a fluid, or possibly, two fluids at the same time. Land vehicles (freight trains, for example) are excluded from this class.

It is a custom among high-performance vehicle aficionados to plot measures of vehicle performance versus speed, often with a family of contours for various payloads and/or stage lengths, for a wide variety of vehicle types, in the manner of Von Karman and Gabrielli, for example, as shown in Figure 1.

The ordinate may be an engineering quantity such as power to weight ratio, drag/lift ratio, some variant of transportation efficiency (for example, hp·hr/ton·mile); or alternatively it may be an explicitly economic quantity such as operating cost per ton mile, required freight rate (RFR), or economic cost of transport, (basically RFR plus a time-value cost on the cargo while in transit.)

Generally, vehicles may be classified meaningfully by which types of lift are involved (for example, static, dynamic, and "powered"), and which fluid (water, air, or both) provides how much of the lift. Typically, the classification of types of lift and the fluids supporting the loads are taken *at cruise speed.* This is an important distinction, because for "takeoffs" and "landings," if any, a different mix of types of lift and fluids (even rubber and concrete) may be involved. For many types of advanced marine vehicles, processes analogous to takeoff and landing are obvious. A representative outline of vehicle types might be as shown in Table 1.

The terminology of static, dynamic, and powered lift is well-entrenched, and seems logical enough for starters. It is the basis of such concepts as the "sustension triangle."

Static lift, we may all agree, comes from differences in static pressure of fluid, acting at different points on a body's surface. Spatial variations in *static* pressure are the result solely of the *weight* of a column of fluid. Therefore, although it's a little odd to put it this way, given the fluid density, *static lift* (*buoyancy* we'd call it) comes from gravity! Dynamic lift, on the other hand, does not.

By dynamic lift, generally, we refer to lift produced by the pressure field created by a body's motion through a fluid. It is a semantic difficulty whether the "body" in question moves along with the vehicle, as is the case of the foil of a fixed-wing aircraft or hydrofoil, or along some other path different from that of the vehicle's center of gravity, say, such as the rotor of a helicopter. This difficulty has been solved, semantically, by restricting the term "dynamic lift" to mean lift from a surface moving along with the vehicle, in the sense of a fixed-wing aircraft, and coining the term "powered lift" to cover other cases, i.e. lift caused by the motion of other parts, rather than the whole vehicle.

"Powered lift" contains its own mysteries, however. It has been argued that several different forms of "powered lift" may be distinguished. To name a few:

(1) The use of engine-driven moving parts to generate dynamic lift by virtue of their velocity, e.g., helicopter rotor blades.

Table 1. Typical taxonomy of vehicles capable of over-water transport.

TYPE OF LIFT (AT CRUISE)	FLUID		
	HYDRO	**AERO**	**AERO/HYDRO**
STATIC	Displacement Hull Mono or Multi, Conventional or Small Waterplane Area; Lim SWA = Submarine	LTA (Airships): Rigid or Pressure	No known species?
DYNAMIC	Fast Planing Hull Mono or Multihull; Hydrofoils	WIGS/Ekranoplan HTA Fixed Wing Aircraft	Very Fast Planing Multihulls; Stub-Wing Flying Boats; Planing Tip Wingships; Windsurfers
"POWERED"	Surface Effect Ships Air Cushion Vehicles	Helicopters Thrust-supported Aircraft	No known species?
MIXED LIFT	Over-driven Disp't or "Semi-Planing," Mono or Multi; HYSWAS/ HYSWAC (S + D Lift)	AEREON ("lifting body airships"), Megalifter (a winged airship) (S + D Lift); HELISTAT, AERO-CRANE (S + P Lift)	No known species?

(2) The use of mechanical or chemical processes to generate what is basically a static pressure field, e.g., a fan increasing the pressure in an air plenum.

(3) The use of a jet (even a rocket) engine to develop thrust which supports the vehicle's weight, e.g., an AV-8 at hover.

Now it may be asked why any of these forms of "powered" lift should be regarded as more "powered" than the "dynamic lift" of the wing of an aircraft being driven through a fluid by an engine, and whether each form perhaps deserves a distinct name to provide a convenient reference to its particular characteristics and behavior. For example, one might use the terms "dynamic powered," or "pseudo-static powered," or "vertical thrust," to refer, broadly, to rotors, cushions, or fluid jets, respectively, when used as lift producers. Even then, there may be subtleties that defy concise definitions. For example, what can be said of the translational lift of a helicopter rotor system?

But regardless of terminology, there is little doubt that static, dynamic, and "powered" lift vehicles must operate very differently. Stated glibly, a vehicle supported by dynamic lift will experience stall or an induced drag "crisis" as it slows down from cruise. A vehicle supported by static lift doesn't. However, purely *static* lift is generally associated with more or less irreducible wetted surface, leading to high drag at high speeds.

Because, typically, all commercial voyages begin and end with a vehicle essentially at rest, *dynamic* lift must be supplemented, and ultimately supplanted, at some sufficiently low speed, by some other form of lift[1]. Stall may not be sudden or catastrophic, but the loss of dynamic lift must ultimately occur, and we better be ready for it. This sad fact can be viewed, in a sense, as the need for landing gear.

Powered lift, specifically of the air-cushion variety, requires a slightly different perspective. While the vehicle may be supported largely, or entirely, by air cushion pressure at all speeds, the question becomes, "What is supporting the cushion?" At low speeds, of course, air-cushion pressure is balanced by static pressure of a water column. At very high speeds, the cushion is not statically supported at all: the water influenced by the air cushion is locally *not* in equilibrium. In effect, this is dynamic lift, too.

So leaving powered lift aside for the moment, and assuming that a vehicle is flying or floating at a constant altitude, total lift can be written in a slightly offbeat form as:

$$L = \rho\, g\, A\, h + \tfrac{1}{2}\rho\, A\, C_L\, V^2 \qquad (1)$$

$$= \rho\, A\, [g\, h + \tfrac{1}{2} C_L\, V^2]$$

where ρ is the fluid density (we assume for simplicity incompressibility, and that the vehicle is small enough to justify taking ρ as a constant), A is a fixed "reference planform area" of the body, h is a "reference height" of the body (which may vary with speed). Thus the first term represents lift due to displacement. The second term represents dynamic lift. C_L is a familiar coefficient which will remain nameless here, in order to avoid confusion, but which is related to the geometry and attitude of the body, and V is the velocity.

Obviously, if two different fluids are involved in lift production, Eq (1) should be given an added pair of terms, for example:

$$L = \rho_1\, g\, A\, h_1 + \rho_2\, g\, A\, h_2 + \tfrac{1}{2}\rho_1\, A\, C_{L1}\, V_1^2 + \tfrac{1}{2}\rho_2\, A\, C_{L2}\, V_2^2$$

[1] E.g. planing boats and hydrofoils both float as displacement craft when at rest.

Formally, this equation is complete enough to cover such rare birds as an airship, nose up for aerodynamic assistance, but with its gondola in the water attempting to plane. Interesting as this concept may be, we will restrict the following development to a single fluid, for simplicity. The mass of the vehicle (including everything inside it, even if it's only air or a lighter-than-air gas) is M. Then by virtue of the assumption of level flight:

$$M = \rho A \ [h + (1/2)\, C_L V^2 / g] \qquad (2)$$

In effect, this equation can be a guide to the required area density of a vehicle. To give a perspective in practical terms, A may be considered as the area of a slip, or of a hangar. The "draft" h must be sufficiently small compared to the available water depth or the vertical clear height in an airship hangar. More to the point, conceptually, h, being also related to a physical dimension of the vehicle, has a direct effect on wetted surface, while the second term in brackets does not. One of the reasons why vehicles operating at the water-air interface are economically interesting is that they provide an opportunity to exchange h (and wetted surface) for $C_L V^2$ as the speed changes, with beneficial effects on drag. This opportunity does not exist in the same way for submarines or blimps.

To oversimplify only a little, on a von Karman-Gabrielli plot, the high speed end is the province of successful dynamic lift vehicles, and the low speed end is the province of successful static lift vehicles. Naively, then, shouldn't the middle of the plot be full of *numerous* successful species of vehicles that derive their lift, at cruise speed, from both sources at once? And if not, why not?

IV. DRAG

The foregoing discussion dealt with lift. What about drag? If the product of lift and speed is associated with paying cargo, or at least value added, then the product of drag and speed is associated with fuel expenditure, that is, cash-flow out. If engines and fuel were the only things we had to pay for, then the goal would obviously be to minimize drag for a given lift and speed. Obviously, economics are not quite that simple: we do have to pay for a hull, or wings, as well, and a few other details, but let's accept the simplification for a moment in the interests of the argument.

The challenge is that drag varies with speed, and with the type of lift. At low speed the lowest-drag form of lift is inevitably buoyancy. At higher speeds, for reasons noted above, the situation changes. But what does this imply about hybrids? For any given cruise speed, in principle, there are only two possible situations:

(1) For practical vehicle configurations, one form of lift will have a significantly better lift to drag ratio than the other

(2) The lift/drag ratios will be about the same

In situation (1), obviously, we should rely on the form of lift with the best L/D to hold up the entire vehicle weight because that will result in the lowest total drag. In situation (2), which tends to be the case in the speed range for which hybrids are a temptation, we might still want to choose one form of lift, for reasons that are described below.

As just one example, consider a high-speed surface ship: a 3,000 nautical mile stage length with a small payload. Consider a high speed displacement monohull (basically similar to a World War II destroyer in geometry), or a large hydrofoil, each with a first-cut estimated weight of about 7000 tons. The L/D ratios turn out to differ only slightly, and the relative advantage of the two forms of lift depend on the selected speed. The destroyer form is a clear winner at 35 knots and the hydrofoil at 50 knots. The displacement hull form has a volumetric coefficient (displaced volume divided by length cubed) of about 1.6×10^{-3} and a waterline length of 540 feet. Such a hull could reach 50 knots on approximately 278,000 shp. Estimating typical weights of hull, machinery, and fuel (calculating fuel consumption at half load) allows for 588 tons of payload. The weights are proportioned from recent destroyer data for structures, and assume a constant weight per SHP for machinery similar to that of current US Navy destroyer gas turbine plants.

Now, we design a 50-50 hybrid for the same speed. Because the hull is supporting only 3500 tons at cruise (with the rest of the weight on the foils), a 540 foot hull is now too long, with excessive wetted surface Consequently, we reduce the length to 450 feet, with the structural weight reduced accordingly. However, we now have foils, and their associated induced, interference, and parasitic drag. Hydrofoil drag is calculated using lifting line theory, with frictional and pressure drag from Hoerner. Assuming a conservative lift coefficient of 0.3 to allow for takeoff, and using two submerged foils, each carrying half of 3500 tons, and adding their drag to that of a 3500 ton hull, we find that the hybrid's power is reduced to 242,000 SHP. The hybrid is also lighter at 6325 LT. One might suppose that the hybrid may have some advantage over a classical "pure" hydrofoil because there are no struts – it is assumed that the hull would be a low block form with the foils attached near the keel.

With payload held constant, the actual power for this hybrid could be reduced somewhat, and the displacement correspondingly reduced, in principle, for the reduction in fuel and engine weights. However, even for the 50-50 hybrid the foils are enormous, the wingspan of a Boeing 727.

Transferring the entire load to the foils, even including estimated strut drags, results in a further decrease to 191,000 SHP. The foils, of course, become nearly twice as big! If we look at the curve of required power against percent of weight dynamically supported, Figure 1, it is clear that the curve is “convex up”; this represents an inherent penalty for having both forms of lift, including interference drag.

Total weight has a similar behavior when plotted against percent of weight dynamically supported, Figure 2. The hull required to support the vehicle at rest and to contain the payload and engines is considerably smaller and lighter than the 7000 ton destroyer or even the 3500 ton hybrid. (The buoyancy of the foils and struts is considerable and was included in the analysis.)

Similar calculations performed for a speed of 35 knots resulted in another pair of curves, but favoring the monohull. For intermediate speeds, the shape of the curve remains convex upward. The hybrid is always non-optimal at cruise, because as the cruise speed is varied, one form of lift has the better marginal performance, and then the other one does. And because of the upward convexity, hybridism is penalized even when the pure forms are equal in performance. If cruise were the only condition, then we would use one type of lift, appropriate for the speed, and hybrid lift vehicles wouldn’t even be a temptation.

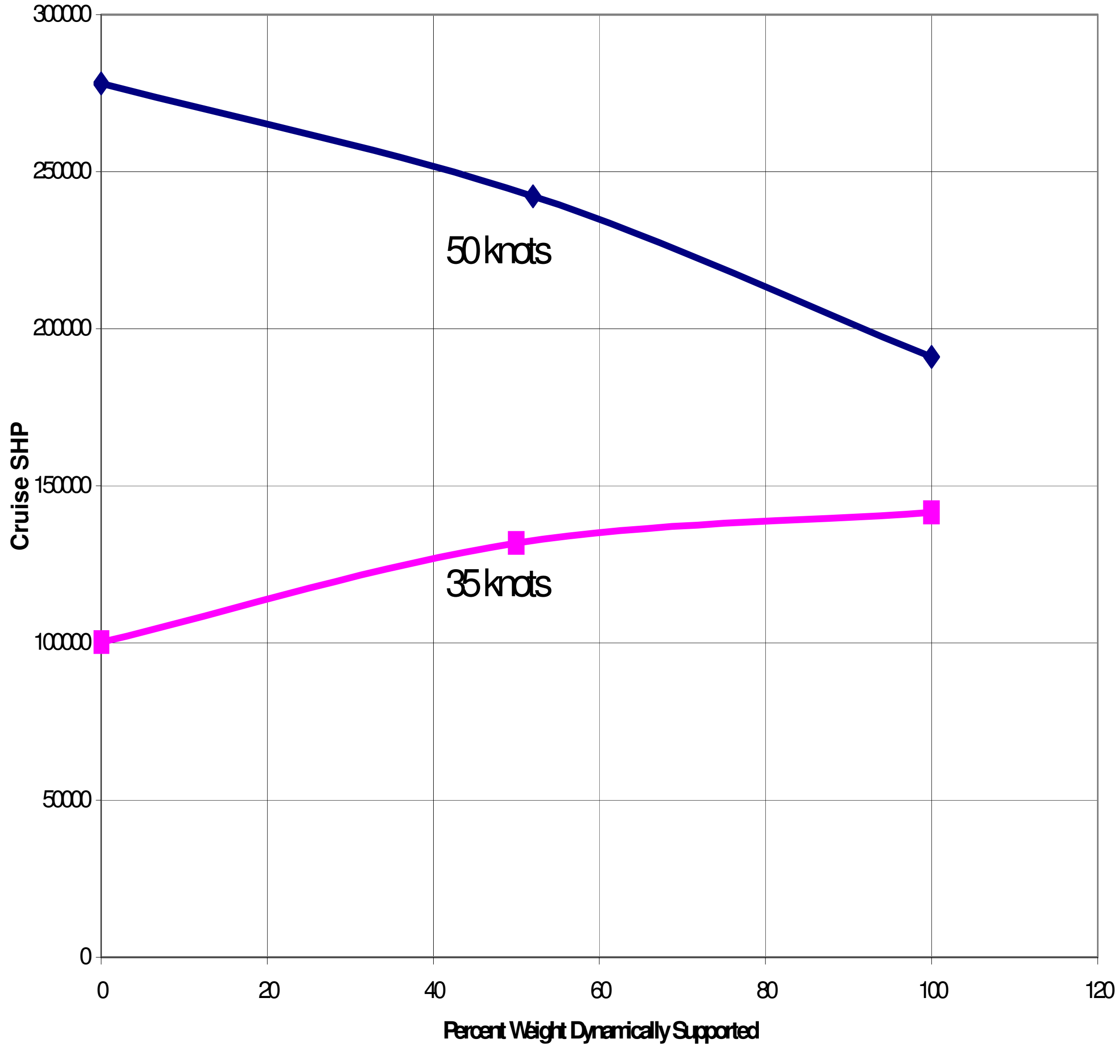

Figure 1. Power versus dynamic lift fraction.

However, even for a line-haul mission, we must get the vehicle up to its cruise speed, and back down again. In many cases what tempts designers toward hybrids is the need to deal with a drag crisis. The simplest example of this is the planing boat resistance hump: very high drag is experienced at a critical Froude number. A similar drag crisis is experienced by dynamically supported vehicles flying at low speeds, just above stall. This may become the point which determines the vehicle's installed power. The engine power required to get over hump may dictate the top speed, rather than the other way around.

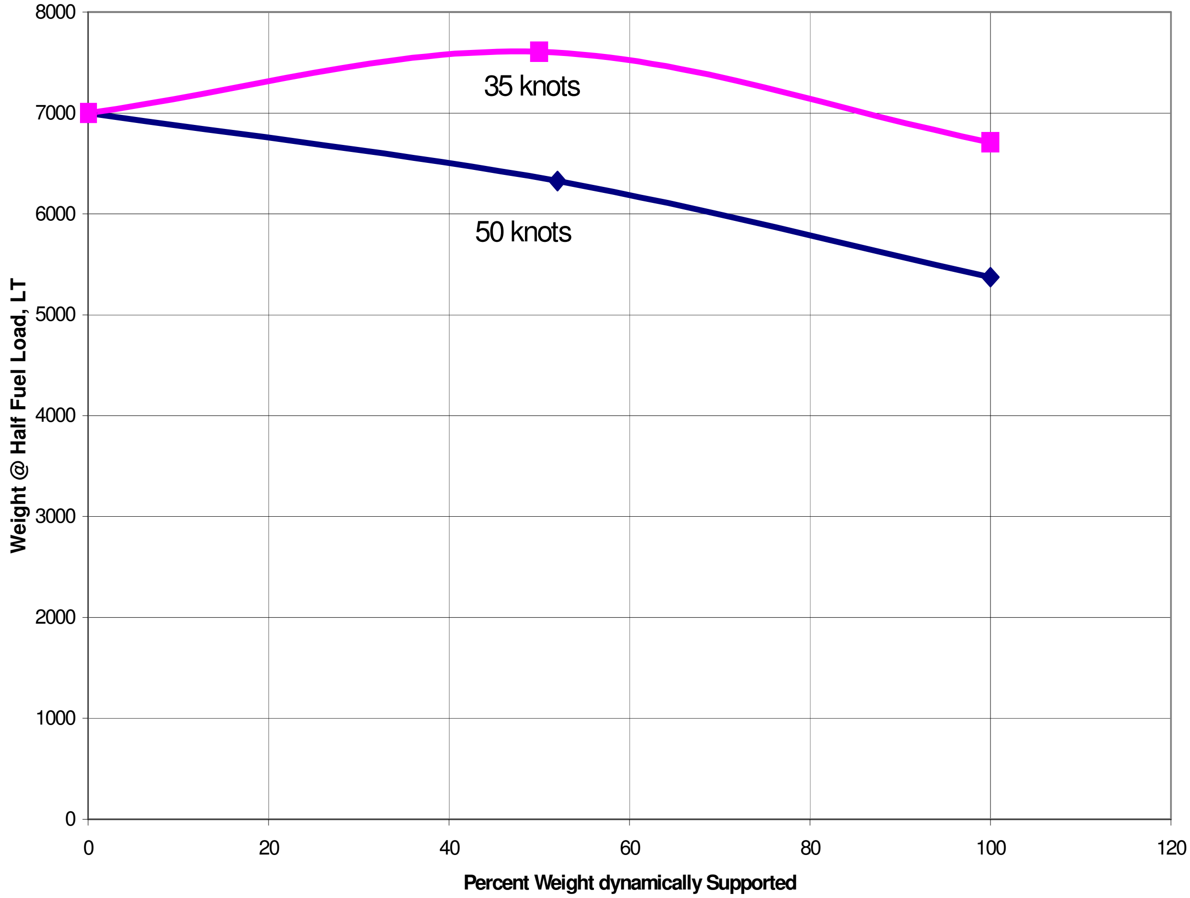

Figure 2. Vehicle weight versus dynamic lift fraction.

The cleanest example the authors can think of is the commercial jetliner. It does make provision for passing through a low speed regime in flight (flaps and slats), but not as a hybrid lift vehicle. It does have a secondary lift-producing system (wheels and tires), which are used for an even lower speed regime, but not in flight. A typical weight fraction for landing gear on an airliner is about 3 percent.

Alternatives to hybrid lift exist for dealing with humps: additional power is one. JATO, catapults, and staged vehicles are other examples of systems used to assist single-lift craft to flying speeds. While alternatives such as these have not been widely used in the marine vehicle setting, the precedent exists: early human-powered hydrofoils were launched by a slingshot. The cruise plant (the human rider) had then merely the task of *maintaining* flight, as opposed to working his way through takeoff and drag hump.

The design question that dominates all such tradeoffs is weight fraction: How much weight (lift capacity) must be dedicated to dealing with drag crises? What is the acceptable weight penalty to pay for a landing gear? A comprehensive answer to this is outside the scope of this paper, as it will differ according to the mission of the vehicle, and the requirements of supporting infrastructure (there are, as yet, no catapult-equipped quays or paved runways on harbor bottoms for the benefit of hydrofoil takeoffs and landings).

However, some observations may be made which may be seen to be obviously axiomatic: the weight of the "landing gear" is subtracted from the payload carrying ability of the craft. Without wheels the airliner could carry a few more passengers or a bit more fuel, or be equipped with a bit less power.

This, of course, immediately leads into the design spiral: eliminating the landing gear will reduce the weight of the craft which will reduce drag which will permit reductions in power which themselves reduce weight and so forth, until a new design convergence is found at a smaller lighter airplane.

In the maritime example we may consider the "landing gear" of the hydrofoil. This is the ship-shaped main hull, which supports the craft during takeoff and landing. It is interesting to compare the ship-like hulls of some hydrofoils with the unusual hulls of the commercial JetFoils – especially when we consider that the JetFoils were developed by an airplane company. Does this choice of hull shape represent an attempt to make the hull form function more vestigial, more of "merely" a landing gear, where other hydrofoil designers have chosen to make hulls which are good ships in their own right? (Think how good a ship a foil-deprived hydrofoil might be. Compare this to how terrible a motor coach a wingless jetliner would be.)

V. THE V-K GAP: PHYSICS OR JUST LACK OF IMAGINATION?

When a typical von Karman-Gabrielli plot is made using a performance variable as the ordinate, such as Kennel's transport factor (*Marine Technology*, July 1998), it is difficult to point out the so-called "von Karman gap." The transport factor of the best types in each speed regime seems fairly well behaved, and the curve proceeds relatively smoothly from one type of lift across to the next. When economic performance is plotted, however, the V-K gap tends to show up as a region where the economics of the best examples fail to follow the progression from low speed and low cost per ton-mile to high speed and high cost per ton-mile. They are all worse.

But if the gap is real, where does it come from? It is our contention that it comes from the nature of lift production. The V-K gap is an unavoidable consequence of one form of lift that experiences stall or an induced drag crisis, and another form that experiences no induced drag crisis but which has a drag penalty at high speed due to excessive wetted surface. There are classes of vehicle that do not seem to have a gap (at least within practical speeds). Freight trains do not. Further, it seems possible that on other planets, with different values of g, or with fluid densities and viscosities widely different from those of water and air, the V-K gap might not be so prominent. But we have to deal with the planet we've got.

It is our contention that attempts to discover vehicles which operates in the heart of the V-K gap, and still makes money, are long shots. It seems to us that there is more to be gained by concentrating on placing the vehicle wholly in one regime or in the other, and then minimize the weight fraction expended on "landing gear."

VI. CONCLUSION

We have taken an unusual and conversational tone in this paper, because our goal is to provoke cogitation. We anticipate – we hope – that we will receive some vigorous discussion and rebuttal. We ask our audience to forgive us our style and consider this message. Put most simply, our beliefs are:

1. A hybrid vehicle combines, not the best of both worlds, but typically the worst of both worlds

2. Some hybridization is required for any dynamically supported vehicle (landing gear are a necessity)

3. The secondary form of lift should be made as vestigial as possible. The best hybrid will be the least balanced, i.e., a 90/10 vehicle is superior to a 50/50 vehicle

4. Application of this thought to modern marine craft may lead to radically new types of vehicles (What does a hydrofoil look like when all other modes of support have been minimized?)