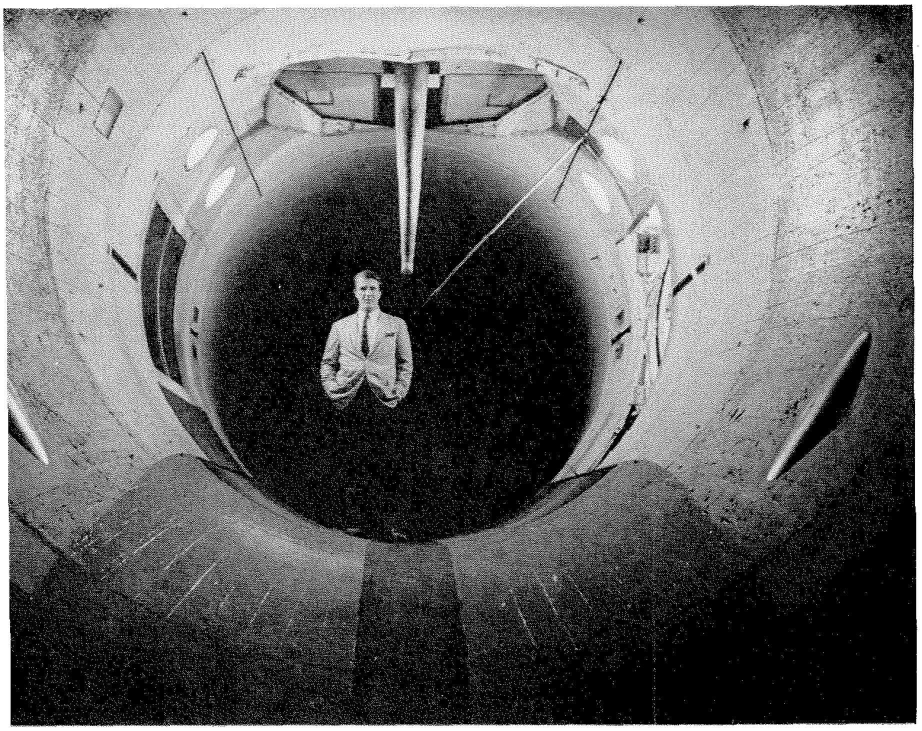


Peter Lissaman, assistant professor of aeronautics, in the GALCIT 10-foot wind tunnel.

The Winds of Change in Aeronautics

by Peter Lissaman

Throughout the centuries man has been obsessed with the thought of being able to travel in the Earth's atmosphere and beyond. From the legend of Icarus to the fantasies of Jules Verne, the mind is constantly stimulated with the prospect of being able to break the bonds tying man to the surface of our own sphere. A multitude of sages has made fantastic and sanguine prophecies of future air and space travel, and yet most of these visions have foundered on the hard facts of physics. The chains of gravity proved hard to break; and it is only in the last half-century that we have been able to sever our links with the nap of the Earth to make possible those ancient visions. The history of man's fight to fly has been described as a "long story, of legends and dreams, theories and fancies, all suddenly transformed into facts; a tale of the hopes of madmen suddenly recognized as reasonable ambitions."

Momentum and the Red Queen

Aerial transport has always lagged behind the predictions made for it because, of all forms of earthbound locomotion, the aircraft is incomparably the most complicated. This is really because it is an interface vehicle, one which travels free from the Earth, but depends upon Earth and its surrounding atmosphere to maintain a precarious equilibrium. The land- or water-based vehicle accepts and concedes to the Earth's gravitational field, and the space vehicle escapes gravity – but the airplane continually defies gravity .

The air vehicle sustains itself by continually pushing air downwards. While it is obvious that a propeller obtains its thrust by pushing air backwards, it is not quite so evident that the wing of an airplane is operating in exactly the same way. It deflects downward the air through which the vehicle is moving to provide a vertical momentum, thus giving the upward force necessary to maintain equilibrium. We may therefore regard the aerial vehicle as a *momentum generator:* a device that operates upon a certain amount of air – the amount depending on its speed and its capture area – and deflects it downwards. The lift it derives from this process depends on the two capture factors, speed and size, as well as the actual density of the air.

Now air is light, and man is heavy, so, because of what Shakespeare called "this insubstantial air," in order to lift our own "too, too solid flesh" we have to handle a great deal of air. This can be done either by using a very large capture area (long wings or rotors), or by traveling at high speeds. The energy or power required to impart the necessary downward momentum depends in a simple way upon the mass of the air. The more air captured, the less downward velocity it need be given, and the less power is required to produce a given lift. Thus, in general, as we reduce our capture mass by making smaller and slower devices, we increase the power required for sustentation.

So, unlike the ship, or hard-surface vehicle, the aerial device must constantly expend power merely to stay aloft. It must then use additional power to move from one point to another against air resistance. Ironically, the power required increases as the vehicle tries to fly very slowly or to hover because the mass of air encountered is reduced so that full engine capacity is usually required for slow flight. The aircraft, in fact, exists in a type of Wonderland where, as the Red Queen said to Alice, "it takes all the running one can do to stay in the same place."

What price speed?

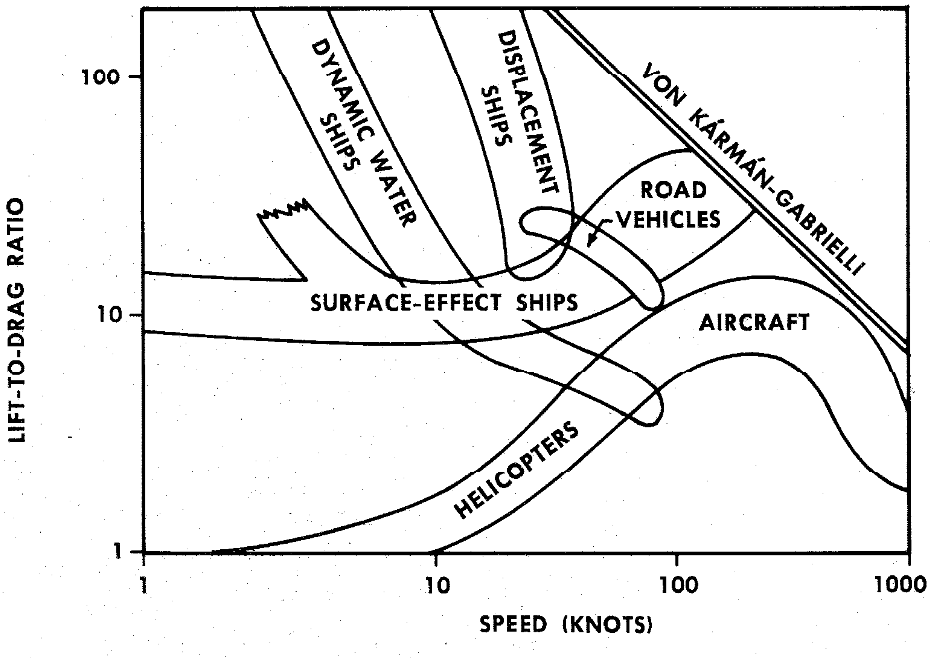
Some years ago, Theodore von Kármán and Giuseppe Gabrielli took to thinking about the myriad means man uses to move himself over the globe, and to analyzing these in terms of transport effectiveness. They produced the graph shown below which compares the speed and lifting translational efficiency (lift-to-drag ratio) of different vehicles.

As can be seen, displacement ships have an exceptionally high translational efficiency right up to 100 and above; it takes a very small amount of power to push a large load at moderate speeds through the ocean. However, to make a ship go fast requires large power expenditures. Beyond about 40 knots, the well-known wave barrier for ships, the power required increases rapidly, and the voyage becomes very bumpy and rough.

Another class of ocean vehicle, the so-called dynamic water ship, is able to break through the 40-knot wave barrier and to approach the 100-knot region, where it starts to get into severe problems of buffet and high drag. These ships rise partially out of the water in cruise and derive a large part of their lift from their forward velocity. One type is the planing boat, of which the best known is the PT boat of the second world war; another is the hydrofoil boat, which is supported by small subsurface hydrodynamic wings, and, as it were, flies through the water. Both consume power simply to stay up, regardless of their motion, so they are intrinsically less efficient than regular ships.

Road vehicles, which include automobiles, buses, and trains, are also less efficient than regular ships because they operate against the friction of the ground; on the other hand, having nothing corresponding to a wave barrier, they can travel faster, their speeds being limited mainly by very physical barriers like people, corners, and other vehicles!

Aircraft always require more power than any other type of vehicle; in particular, aircraft that are designed to travel very slowly, like helicopters, have



Lift-to-drag ratio is a measure of the effectiveness of different vehicles. For a given speed, the vehicle highest on the chart will have the best transportation effectiveness.

(After Von Kármán and Gabrielli.)

a very low translational efficiency. However, as the speed of an aircraft increases, so does its translational efficiency, up to about 600 knots, when the airplane starts to meet its own wave barrier, the speed of sound. At that point the drag increases severely, and the efficiency falls off.

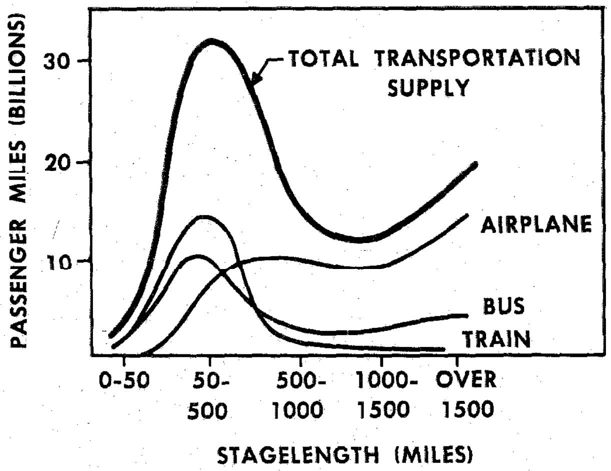
Von Kármán and Gabrielli proposed, on a purely statistical basis, a line which they suggested was the absolute limit for transport effectiveness. And, interestingly enough, very few vehicles have succeeded in crossing that line. However, a curious class of vessels, called surface-effect ships, falls in a region not covered by either airplanes or ships, and holds great promise.

The important thing about transport is that one always pays a price for speed. However, in some areas one gets a better bargain for one's money, especially when one operates close to the limiting line. Therefore, for about the 150- to 600-knot range, aircraft are the best mode of travel; for about the 40- to 150-knot range, surface-effect ships; and below 40 knots, displacement ships.

A statistical picture of people's demands and habits of perambulation shows two very significant factors: (1) the enormous demand in the 500-mile range, and (2) the fact that the airplane does not have its share of this traffic.

These curves have been drawn for the highly mobile and technological society of the United States. Similar data from the underdeveloped countries or from the intensely populated regions of Western Europe would show an even more striking illustration of the great gap that can be filled only by air transportation.

Consider those great land masses of India, Africa, and South America: continents that awoke after the Industrial Revolution, that do not have the inland waterways suitable for hydro transportation, and that struggle with overcrowded rail and road systems to move their teeming peoples. It is too late in history to build railroads, to cut so painfully slowly across the Earth's face. But the Huntingtons, the Stanfords, of a new age are already living, and to them the Amazonian jungle and escarpments of the Drakensberg are Sierras of the mind; from 15,000 feet they are merely marks on a map. Above those virgin lands lie the vast and limitless highways of the skies. The benefits to the underdeveloped countries of a comprehensive and efficient air transport system stagger the imagination; because of the topographic barriers to surface travel, they have no way to go but *up* in the literal sense of the word.



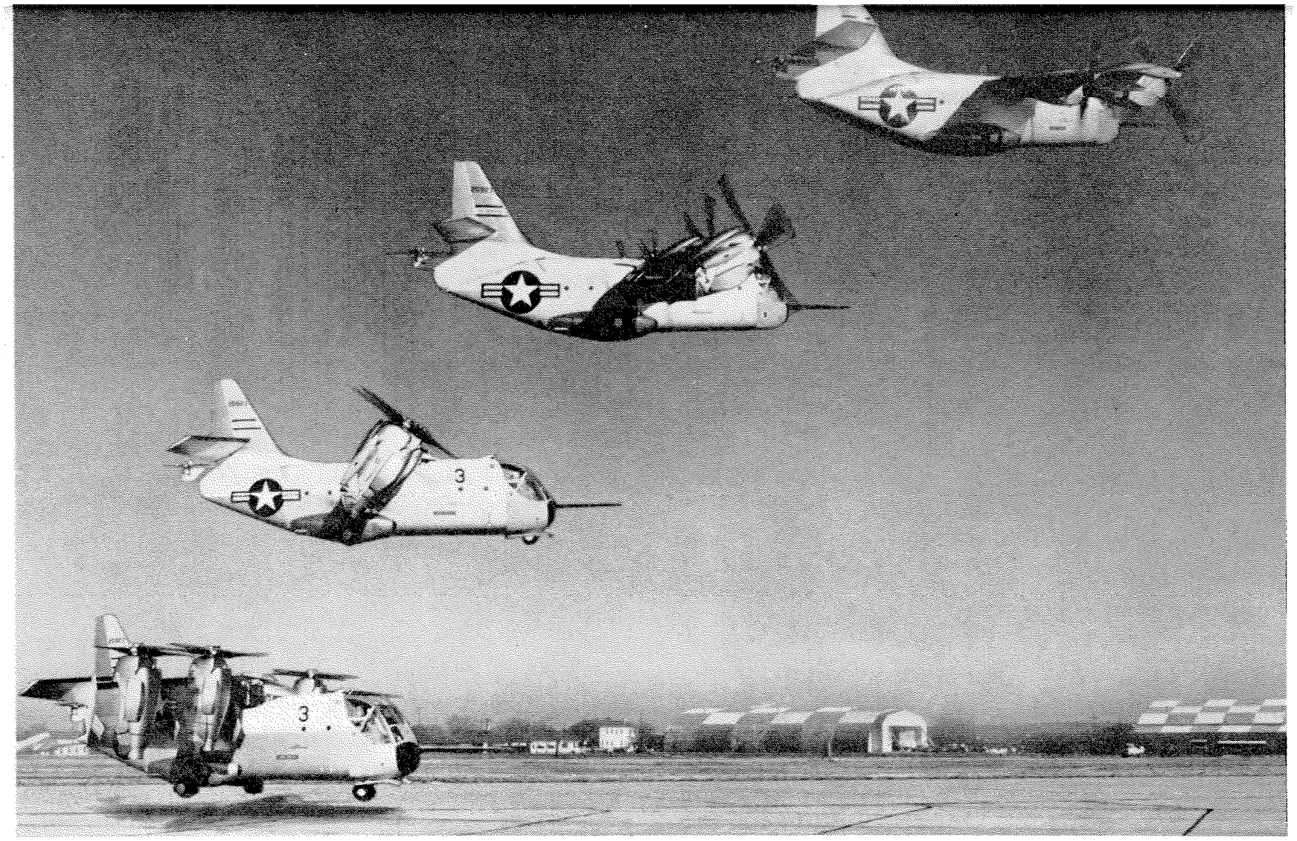
Transportation spectrum, showing how demands for various-length journeys are met in the United States.

Consider for a moment what can be done using conventional aircraft. The great C5-A transport airplane, commissioned this October by the U.S. Government, will carry a quarter of a million pounds over stagelengths of thousands of miles at speeds in excess of 500 knots. One of these airplanes can do the same transportation job as a 50-car freight train. To be sure, it will still cost less to transport certain goods — timber, steel, sides of bacon — by surface vehicle; flying is expensive for pigs. But if one demands more salubrious accommodations than would a side of bacon, the cost comparison is remarkable. Projected C5-A passenger versions give transcontinental airfares at levels comparable to bus rates and make the $100 Atlantic crossing look quite feasible.

This is a look at the future for high-density, long-range routes with advanced terminal facilities at either end. However, present demand for the intercontinental stagelength journey is still fairly low, particularly on a world-wide basis. In the 50- to 500-mile range a new type of aerial conveyance is needed. It will look quite different from the conventional bird-like airplane, since it must possess performance characteristics that in the past we have been unable to achieve.

Low, slow, and safely

The reason that aeronautics has not, up to now, provided the vehicles for mass transportation lies in the serious terminal problems of modern high-speed aircraft. The jet airplane is a marvelous device for traveling comfortably and speedily from A to B. There is no more effective way to pass from Tehachapi to Leadville — provided you don't want to get on or off at either of these spots. The modern subsonic jet has its major failing in its landing and take-off requirements — which are immense and rapidly



A composite photograph of the XC-142, a highly promising V/STOL aircraft, showing the stages of transition flight.

becoming more severe. These involve large, costly airports which are noisy and far from cities, and high landing and take-off speeds which greatly increase the danger, especially in conditions of marginal visibility.

For decades we have realized that the answer to this was a vehicle that could alight vertically or at a very low forward speed (the vertical/short take-off and land aircraft – V/STOL); but to design such a machine is an extremely difficult technological task because of both the high power requirements and the stability problems. Our current answer is the helicopter, which today has been carried to the limit of its development in its present form, as has the fixed-wing airplane.

The helicopter, which performs admirably as a VTOL, is seriously limited in maximum speeds. At higher speeds those great flapping blades, so essential to enable it to capture the air mass required for hovering flight, become a high drag encumbrance. It appears as though 200 knots may be about the limiting speed of the craft in its conventional form; but even this is remarkable when one considers that half the rotor blades are still going backwards when most of the machine is lumbering haphazardly forward. To see a helicopter in high-speed forward flight reminds one irresistibly of the romantic character who "flung himself upon his horse and rode madly off in all directions." The problems of the fixed-wing airplane at low speeds are well known; a very high proportion of aircraft accidents are caused by low-speed stall.

Airplanes and helicopters are at the threshold of a new wave of development in aeronautics, which consists, in essence, of controlling the external airflow, not only by geometrical techniques (with rigid flying surfaces), but also by the addition and subtraction of tailored high-energy air. Today circumstances are ripe for a new revolution in aeronautics which could finally bring cheap travel within the reach of Everyman. The three new ingredients of this mix are:

(1) The need exists and is recognized.

(2) The means of producing auxiliary airflow is available in the gas turbine.

(3) The technological ability to handle the complex theoretical problems involved is within our grasp.

One proposed solution to the problem of V/STOL is the Ling-Temco-Vought XC-142, a vehicle that very obviously combines the characteristics of the helicopter and the airplane. It is undoubtedly a complicated machine, expensive to build and operate, and difficult to fly. But it represents a firm step in the direction of V/STOL transport.

The tiltwing vehicle, of which the XC-142 is an outstandingly successful example, is a very direct approach to the problem of forcing air downwards by means of rotating machinery, having given up hope of doing it with a fixed wing or vane. However, extensive work is in progress in attempts to get the air to adhere to a surface even while turning through very large angles (in other words, to prevent stalling). This involves flow control, in the form of *boundary layer control* and the *jet flap*.

Flow control

It has long been known that when a surface moved through a fluid it was surrounded by a layer of slow-moving air which, in effect, stuck to the wing. This sheet of low-energy air, of the order of ¼-inch thick on a conventional wing, is known as the boundary layer, and is the root of all the problems associated with stall.

As the angle of attack of the wing is increased, the boundary layer air on the upper surface becomes progressively more sluggish until it is unable to make the passage to the back or trailing edge of the wing, and separates from the surface to mix with the main airstream. When this happens, the air on the upper surface no longer flows down along the wing itself, but streams straight backwards with the main airflow. Thus, the lift of the upper surface is lost, usually quite abruptly and with catastrophic consequences, and the wing is said to be stalled.

The most fundamental way to eliminate this problem is to get rid of the low-energy air in the boundary layer. This can be done by perforating the wing surface with a multitude of tiny holes or slots. Now, curiously, the desired result can be achieved either by blowing or sucking through these orifices. In the first case, a high-energy flow is blown out from the wing interior, which rejuvenates the sluggish boundary layer; in the latter, the low-energy air layer is sucked away into the interior of the wing, thus foiling its reactionary tendencies. The second method consumes appreciably less power. However, the main operational applications of boundary layer control have been in the use of the blowing philosophy, where a high-energy jet is blown over portions of the wing upper surface. This technique is used successfully in some naval aircraft, with their notoriously severe carrier landing problems. While it is true that blowing requires considerably more power input, it is easier and it works.

A more elegant and sophisticated approach to the high-lift problem is to blow a very high energy sheet of air backwards and downwards from the entire trailing edge of the wing. This both ameliorates the stall problem and creates an effective artificial wing many times larger than the actual rigid wing surface. This device is known as the jet flap. Extensive theoretical and experimental work is being done in this field in Europe, and the problem is also being studied at Caltech. Because of some peculiar advantages, it could be the next step in STOL aircraft.

The most striking thing about the jet flap is the phenomenon called the *thrust paradox*. It is so named because it seems like one of those rare but delightful occasions when one gets something for nothing. The jet sheet leaving the wing is directed downwards, and thus contributes appreciably to the lift; however, as it progresses downstream it is gradually turned by the oncoming air until it is finally going almost horizontally, so that the momentum is now directed backwards and provides the thrust necessary to propel the aircraft. Thus we first obtain lift from the air jet and then, most obligingly, it turns to provide thrust. The extra lift of a possible jet-flap aircraft may be five or six times that of a plain wing, and is obtained at little extra power cost. The significance of this development can be realized when one notes that up to now all airplanes have been, essentially, powered gliders. In other words, they consist of a lifting system (the wing) to which is bolted, with more or less elegance, a thrust system (the engines). In the jet flap we have a fully integrated flight system, one in which lift and thrust are developed simultaneously — a principle our feathered friends have used for centuries.

A further promising application of the jet-flap principle is to the helicopter. Here we envisage a wide rotor blade emitting the jet curtain all along its trailing edge — the jet thrust provides the torque necessary to turn the rotors, while the highly efficient lifting characteristics eliminate or avoid blade stall, one of the major factors militating against high-speed helicopter operations. Very recent theoretical work in this field has suggested that a helicopter with jet-driven and -controlled rotors could achieve speeds of the order of 300 knots. Alternatively, in the design of a device for operation at lower speeds, it seems that the jet-flap rotor might have other very desirable characteristics: reduction of mechanical complexity, increased engine-out safety, and lower noise levels.

It has been known for many years that when a wing flew close to the ground its lift was increased by a small amount, because of a cushion of air built up underneath the lifting surface. This effect is much more pronounced in the case of the jet-flapped wing, which makes the device even more effective close to the ground when, of course, the high-lift properties are most desirable.

It seems endemic to human nature that when one is on to a good thing one cannot resist carrying it to

continued on page 20

A foretaste of things to come—a Hovercraft ground-effect machine, now in commercial use on San Francisco Bay.

ridiculous extremes. Therefore, it was only natural for someone to think of operating a jet-flapped wing in very close proximity to the ground – and thus was born one of the few radically different lifting vehicles of this decade, the ground-effect machine (GEM) or Hovercraft which is generically known as a surface-effect ship.

Surface-effect ships

Throughout the centuries man has waged an unremitting, and to a large extent successful, battle against friction. One major step was when he decided to roll rather than slide and invented the wheel; the next great step was when he lifted himself from the ground and was able to escape even rolling resistance. In aerial navigation he was retarded only by the insubstantial air and was able to achieve undreamed-of speeds, but always at the cost of the power required to stay aloft.

By operating very close to the ground we can greatly reduce this power and still move almost without resistance on a cushion of air. GEMs blow out a high-energy curtain of air around their periphery, thus trapping a high-pressure air bubble beneath them and the ground upon which they float. Of course, they cannot rise very high off the ground; current heights are scarcely more than a foot or two, but this lift is obtained at very low power cost. These vehicles can operate at high speeds, of the order of 100 knots, very cheaply, and provide a most attractive means of high-speed surface travel in a region that lies essentially between land vehicles and airplanes, and thus fill an important gap in the transportation spectrum. Moreover, because the vehicles travel equally well over land or water, they can deposit passengers right at city centers.

Fresh winds in aeronautics

The developments discussed here involve some of the more important movements in modern subsonic aeronautics. We have come to the end of a phase – one that started with man's first fragile flutterings and ends with his thrusting of white-hot supersonic vehicles through the audibly protesting air. It seems now that the time of brute force is over; we are realizing that air must be coaxed and induced, rather than forced to serve our ends, and that this can be done most elegantly by molding the airflow with auxiliary airstreams. We now have the ability to change completely the face of the world transportation spectrum by intelligent use of new techniques of lift and propulsion. This will be a change that will place travel and mobility within the reach of the common man – that will bring us commercial, educational, and human gains of enormous significance, and may finally realize the Wright Brothers' old and noble dream of "aeronautics as a benefit to the peoples of the world."