Getting Grounded

Safely and Intentionally. This is the first in a series on landing gear considerations.

BY FORBES AIRD

Here's a snap quiz: given equivalence in powerplant, prop and total weight, which will have better performance in the air: a landplane or a seaplane?

Right. Now, why?

Betcha said something about the aerodynamic drag of floats, about the difference between shapes capable of operation on water versus those optimized for air; betcha used the word *compromise*. But landplanes no less than seaplanes operate in or on two media, only one of which is air, and while the need to roll compromises flying less than the need to float, let there be no doubt that there is compromise aplenty.

What we're leading up to is the design of landing gear.

Does the rolling, for instance, take place on pavement or off? How do you feed two very large point loads (coming through the main landing-gear attachments) into a structure otherwise supported by widely distributed forces? Is the weight penalty of retractable gear—and the inevitable decrease in pilot error tolerance and systems reliability—justified by the reduction of aerodynamic drag?

Because they stick down into the airstream or up into the airframe, wheels, brakes, tires and other components should be as small as possible . . . but how small is that? And what about wheelpants? Certainly, their weight is minimal and very likely will yield benefit in the air, but they may cause those small tires and brakes to overheat. They also tend to inhibit inspection and maintenance. And finally, on which end of the airplane are you going to put the third wheel?

Even very clever designers have nightmares wrestling with such issues, and we haven't even touched on the really important part: is the thing going to be manageable on the ground? In this series of articles on landing gear, we'll be looking at these tradeoffs, considering the requirements of a satisfactory landing gear design in terms of the earth-bound handling behavior of the aircraft—including its ride qualities, to the extent they affect handling.

Think of an aircraft moving on the ground as a highly compromised automobile. Yet an automobile engineer would quake at the assignment of designing a suspension and steering system once the requirements are spelled out: "When it's not actually flying, this sucker rumbles along the ground—which may be good pavement or someone's lawn—at anything up to 70 or 80 mph, perched three feet high. Full, it weighs about one Volkswagen worth, but the load on the wheels varies from maximum to nothing, roughly inversely proportionate to the speed, and sometimes it gets dropped violently, at high speed. Depending on whether the tanks are full or empty, much of the weight may be way out there at the sides in those whatchemacallums. Then again, it may not.

"This machine should ride and handle nicely full or empty, and we need to be able to really clap on the brakes if we start to run out of, ah, lawn, without ripping the wheels off or tipping over onto those fan blades at the front. Oh, did we mention that the whole suspension and steering system should fold up into a couple of suitcases? It's also kind of important that it unfold on cue, every time. Here's these two wheelbarrow tires and a castor off a patio barbecue to work with. Go to it, and good luck!"

The automobile engineer might approach the situation by comparing light aircraft and automobiles. If astute, he would soon spot some analogies between tires and airfoils. Both are obviously the principal means by which forces are applied to the vehicle as a whole but, more than that, an inspection of their *characteristic curves*—the relationship between certain input conditions and the force output—reveals some highly informative similarities. (See Figure 1.)

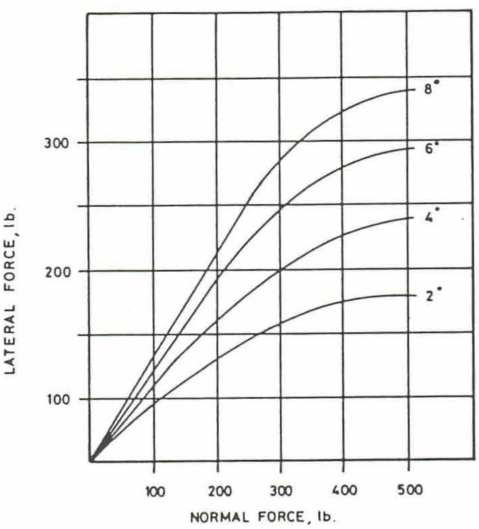


Figure 2. Variation of lateral tire force with normal force at various slip angles.

Working from the familiar rudiments of wing theory, the analogy runs as follows: tires generate forces at right angles to their direction of travel when operated at some small angle to that line, just as airfoils develop lift when angled to an oncoming airstream. The angle of incidence is called a *slip angle* when it pertains to tires. In view of the universal free-lunch rule, it should come as no surprise that there is in both cases a drag force that acts to retard the overall vehicle motion. There is also an unbalanced torque, analogous to the *pitching moment* of airfoils, known in tire language as *self-aligning torque*.

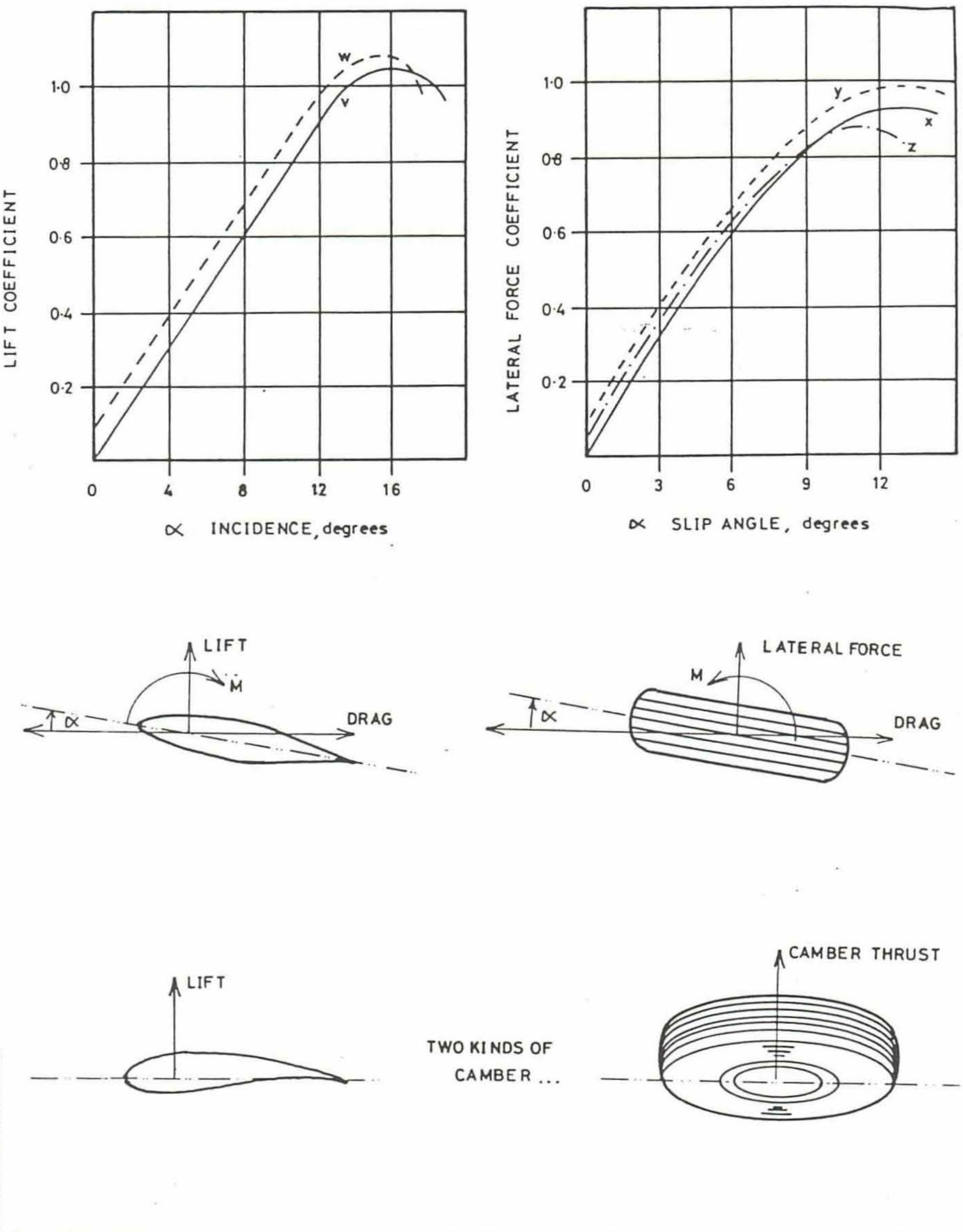
In each case, there is also an operating range over which the characteristic curve is essentially straight, with a roll-off at some upper limit. The upper limit, which represents *stall* in the case of airfoils, is called *skidding* in the case of tires. At the risk of straining the analogy and causing confusion, there is also a correspondence in the effect (though not the definition) of *camber*. In airfoil terminology, camber is a curvature of the mean line; in tire-talk, camber is an inclination of the wheel/tire assembly away from perpendicular. In both cases, however, the effect is biased behavior: a cambered airfoil generates lift even at apparently zero incidence; and a cambered wheel/tire assembly generates a sideways force even at zero slip-angle, that is, when it is not steered.

Well, this is all very neat and tidy: we've got analogues for lift, drag, pitching moment, incidence, camber and stall. So we just treat tires like round, black, ground-captive wings, sort of running on their sides, right? Not quite. There are some awkward bits to sort out before you can pack up your concepts in your old kit bag.

Remember those *dimensionless coefficients* from Figure 1? Look again. In the case of the airfoil, you reckon total lift from the (lift) coefficient, times area, times the velocity squared. In the case of the tire, the lateral force is calculated from the (lateral force) coefficient times the normal force acting between the ground and the tire; velocity is not involved. (Actually, tires *are* speed sensitive, but only very slightly.)

In one specific respect, the velocity-dependence of airfoils and the independence of tire forces is self-cancelling. When an aircraft touches down and begins to roll out, the available aerodynamic forces rapidly dwindle away according to the square law as the speed bleeds off. At the same time that the rudder effectiveness decays, however, the wings are unburdening themselves onto the wheels and tires, so the available tire forces are increasing as the wheel/tire assemblies are pressed harder onto the ground.

However, the lateral force produced by a tire at any given slip angle is only *approximately* proportional to its vertical load. A plot of the two effects (Figure 2) reveals that while they are nearly linear over a limited range, increments in normal force yield progressively smaller increments in lateral

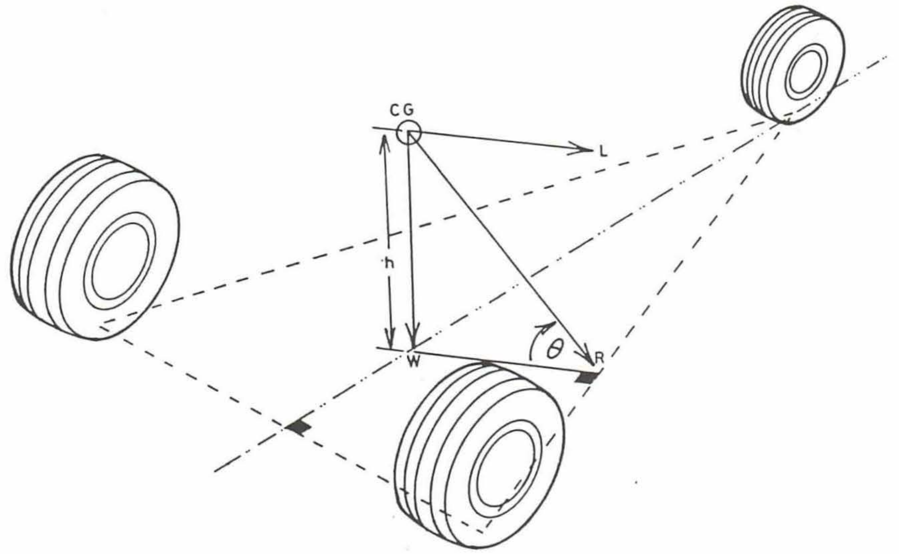


Illustrations: Forbes Aird

Figure 1. Analogy between airfoils and tires. Curve V is for a typical symmetrical airfoil; curve W is for an airfoil with a curved (cambered) mean line. Curve X is for a rounded-tread tire; curve Y is for the tire cambered (tilted) slightly. Reduced tire contact from tilting eventually offsets camber.

force output. A consequence of this is that a *pair* of tires sharing a load can potentially generate the largest lateral force when they share the load *equally*. Any uneven division of the load, such as will occur with any lateral weight transfer, will reduce the total force produced by the pair, since the one more heavily loaded will "gain" less than the other one "loses."

Another complicating factor is that both the departure from linearity of this load/force plot and the coefficient itself also depend on the inflation pressure of the tire. Yet another variable is the presence or absence of any longitudinal thrust that may be demanded of the tire. It is a useful first approximation to regard the force that a tire can exert as being a vector that may be directed anywhere, but which is fixed in magnitude. A tire called upon to produce a braking force cannot generate as large a side force as one that is free rolling; and as the braking effort approaches the limit where the tire begins to slide, the potential lateral force is reduced to zero. Do not suppose, therefore, that the transition from flying to driving



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(and vice versa) is simple from the whole steering/stability point of view.

Reverting to the point of view of our hypothetical automobile engineer, the most obvious kind of stability is the ability to keep the shiny side up. This requires that the mass center lie within the triangle connecting the points of ground contact. Otherwise the vehicle would tip over. The mass center also is situated some considerable height above the ground, and since the wheel/tire assemblies can apply forces only in the plane on the ground, all tire forces will result in some weight transfer between tires. This reduces the lateral force potential of the pair of tires, as we have seen. More importantly, if the resultant of these force shifts ever falls outside the ground-contact triangle, overturning will result. To avoid this, the mass center must be sufficiently low and sufficiently far from the perimeter of the triangle that the tire forces cannot induce capsize. See Figure 3.

In practice, such considerations as propeller clearance will demand some compromise to this ideal, leading to more-or-less arbitrary limits on the overturning angle. Although the grip of the tires will be greatest on smooth pavement, experience has demonstrated that most bumps have a lateral component and so, paradoxically, the value of the overturning angle for rough field work will be somewhat less than that for smooth pavement, to ensure that the tires do not routinely generate enough force to put the whole business on its head.

Figure 3. Keeping the vehicle upright. If the resultant (R) of gravity (W) and lateral force (L) falls outside the ground-contact triangle, the vehicle turns over. Height of the c.g. (h), resultant angle and magnitude of lateral force (L) determine the result.

It is of course necessary to stay right side up, but it is hardly sufficient: it is also vital that the vehicle be capable of following a predictable path. A useful general definition of directional stability—both airborne and landborne—is that after any small, brief disturbance of its motion, whether from a momentary control input or from an external force such as a gust or bump, the vehicle should respond by taking up a new steady path without further action by the helmsman.

Consider, for a moment, the similarity between deflection of the elevators or ailerons of an aircraft and steering of the front wheels of an automobile. Generally, what is going on is that operation of the controls does *not* directly modify the path of the vehicle; rather, it modifies its *attitude*, which thus steers the tires or wings with respect to the operating medium (ground or air). It is this change in incidence of the tires/wings that produces the reaction forces which in turn deflect the vehicle as a whole from a straight-line path. What we're after, then, in both cases, is that any change in vehicle attitude should produce forces that yield a stable new path—whether straight or curved—for the vehicle as a whole.

Having said that, we won't get any further into aerodynamic stability than we have to, but let's consider the ramifications of this definition for a wheeled vehicle—more particularly a three-wheeled vehicle. Let's look first at the case of a taildragger rolling straight ahead on all three wheels. Any slight lateral disturbance that causes the craft to adopt some small yaw angle means that the front (main-wheel) tires are operating at some slip angle and are therefore generating a corresponding side force. Now, this force acts *ahead* of the mass center, shoving the front of the vehicle toward one side so the vehicle begins to diverge from its original straight-line path. Once cocked off even slightly, braking forces exerted by the main-wheel tires, even their rolling resistance, will also contribute to the destabilizing moment around the mass center (see Figure 4). If the tailwheel is free-swivelling, it will be unable to produce any balancing force, so the yaw angle grows, which increases the force exerted by the front tires, which causes the vehicle to yaw even further. Barring hasty intervention by the driver, the cycle winds up, faster and faster, and the resulting ground path is a curve of ever-tightening radius: the familiar groundloop, the ultimate expression of divergent instability of yaw.

The fixes are as familiar as the problem: restrain the tailwheel from swivelling, either by locking it in the straight-ahead position, or with centering springs of some sort. Then, provided that the moment produced by the force of the more-or-less fixed tailwheel, multiplied by its distance from the mass center, at least slightly exceeds the yawing moment produced by the main wheels, some stable path will result.

This is not to say that the vehicle will just bobble a little bit and then resume its original course. If the tailwheel is fixed straight ahead, the new path will be a straight line at an angle to the original. If it is spring centered, the result theoretically will be a succession of S-curve oscillations superimposed on a curve of constant radius . . . provided that the centering springs are relatively stiff. If the springs are insufficiently stiff, the tailwheel will act basically as if it were free, and if the tailwheel is unloaded by braking or by elevator forces, it will be similarly unable to provide any restoring force. In either case, our condition for stability is not met.

So we know taildraggers with free-swivelling tailwheels are unstable on rollout. So what? A *real* flier can keep steering with the rudder until slowing to walking pace and then just tip-tap those brakes smoothly. . . . Besides, if you want stability, get a wimpy tricycle-gear craft like they rent to those with well-waxed penny loafers. One wheel at the front spells stability, right? Wrong again, sport.

So far, we have ignored corrective aerodynamic force inputs. Given enough windage and enough rudder, you could shove a dumptruck plumb sideways, no matter what its tires were doing. We're trying to establish how a *ground* vehicle behaves, depending entirely on tire forces, assuming no aero inputs at all, and presuming the driver to be absent, paralyzed with fear or equivalent. As for the directional stability of tricycle gear, we have to go back to our general principle: the tire(s) behind the mass center have to be capable of generating a larger moment about the c.g. than that produced by the tire(s) in front. If the nosewheel is free-swivelling, that result is guaranteed . . . but that makes the resulting vehicle, like a taildragger, dirigible only by aerodynamic means or by differential braking on the remaining pair of tires; much of the virtue of tricycle gear is its automobile-like steering behavior during low-speed maneuvering.

To steer in the usual automotive sense, the front wheels are deflected to operate at some slip angle, so the front of the vehicle is given a push in the appropriate direction. The resulting yaw then obliges the rear wheels to develop a slip angle of their own, which gives a corresponding sideways shove at the rear. If the shoves at front and back produce equal moments around the c.g., the vehicle will receive a purely sideways push, with no tendency to turn around its own c.g. This will yield a steady, straight-line path if there is a countervailing force, such as a crosswind; otherwise the vehicle will adopt a steady circular path. Note, however, that the front wheel is still steered through some angle, relative to the rest of the vehicle.

For path stability under these circumstances, that is, for the moments generated by the back end to match those at the front, the rear parts must produce the requisite force at a slip angle smaller than that at the front. Should that condition not be met,

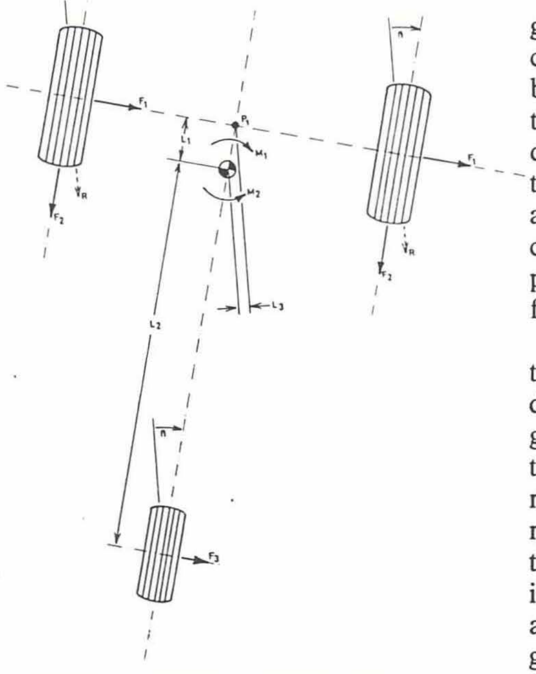

Figure 4. Avoiding groundloops. Moment M_1 is produced by tire slip angle (β) resulting in lateral force F_1. Tire drag and braking force, acting through length L, also contribute. Whether yaw continues depends on the restoring force (M_2) produced by third-tire force F_3 acting through length L_2. F_3 will be negligible if it is a free-swivelling tailwheel or is unloaded by elevator.

either the helmsman is obliged to back off somewhat on the steer angle to permit the stern to "catch up" with the bow, or the vehicle must continue to crab around until something akin to a groundloop occurs. Under heavy braking on a tricycle, for instance, the lateral force potential of the rear tires will be dramatically reduced by the longitudinal force they are being called on to provide. At the same time, the grip of the rear wheels is being reduced (and that of the front/nosewheel increased) by longitudinal load transfer. Under these circumstances, the directional stability of the tricycle is by no means assured.

In truth, there are some other factors which might also intervene: remember that *cambering* causes tires to generate forces not directly related to slip-angle. The geometry of the suspension may be designed to take advantage of this effect by providing for favorable camber change as the load transfer mentioned above compresses the spring on the outside of the curve. Enabling the more heavily loaded outside wheel/tire assembly to generate a suitably greater side force could bring everything into equilibrium. A similar effect may occur if the geometry—either by accident or design—causes the wheel/tire assembly to *toe-in*—to steer in the same sense as the front end, as the spring is compressed. (*Toe-out* is the opposite phenomenon—wheels steered away from the vehicle centerline.)

Both this *roll-steer* and camber thrust take some time to develop, depending as they do on the overall gross motion of the vehicle, and the time that this takes depends on the roll moment of inertia. It would require a lengthy numerical analysis to determine if these potential restoring forces would arrive in time to do any good. Far better is to ensure that ground path stability is derived from inherently greater cornering power on the tires behind the mass center.

But if the lateral force developed by a tire is a function of the normal force acting between it and the ground, and on the slip angle, moving the mass center back and forth should have no effect on directional stability, since the supply and demand remain in lock-step. Clearly, the balance of normal forces front and rear can be modified by the elevator but, remembering that we are trying to examine what is going on *in the absence of aerodynamic forces*, you might well wonder just how otherwise to arrange for differences in the moments generated by the tires. If you have been following closely, you will see that the answer lies in the fine print. The only means available to produce tire force moments about the mass center that do not inherently balance themselves out (and that do not, like camber change, depend on the overall motion of the vehicle) is by the tailoring of tire sizes, inflation pressure, static camber and static toe-in/toe-out and by taking account of the reduction in the available lateral force from a *pair* of tires that occurs as a result of load transfer whenever the vehicle is subject to side forces originating at the tires. So now you know another reason why the nosewheel is smaller than the others!

Next month we'll look at how various means of attaching the wheels to the aircraft can affect stability through camber and changes in toe-in/toe-out. We'll also go into some detail about springs and damping, both in terms of ride quality and from the point of view of materials selection. □