Weight And Balance—Why

Center of gravity can affect flight characteristics but needn't be a bugaboo. This article tells you how to use 'cg' and place it in proper perspective

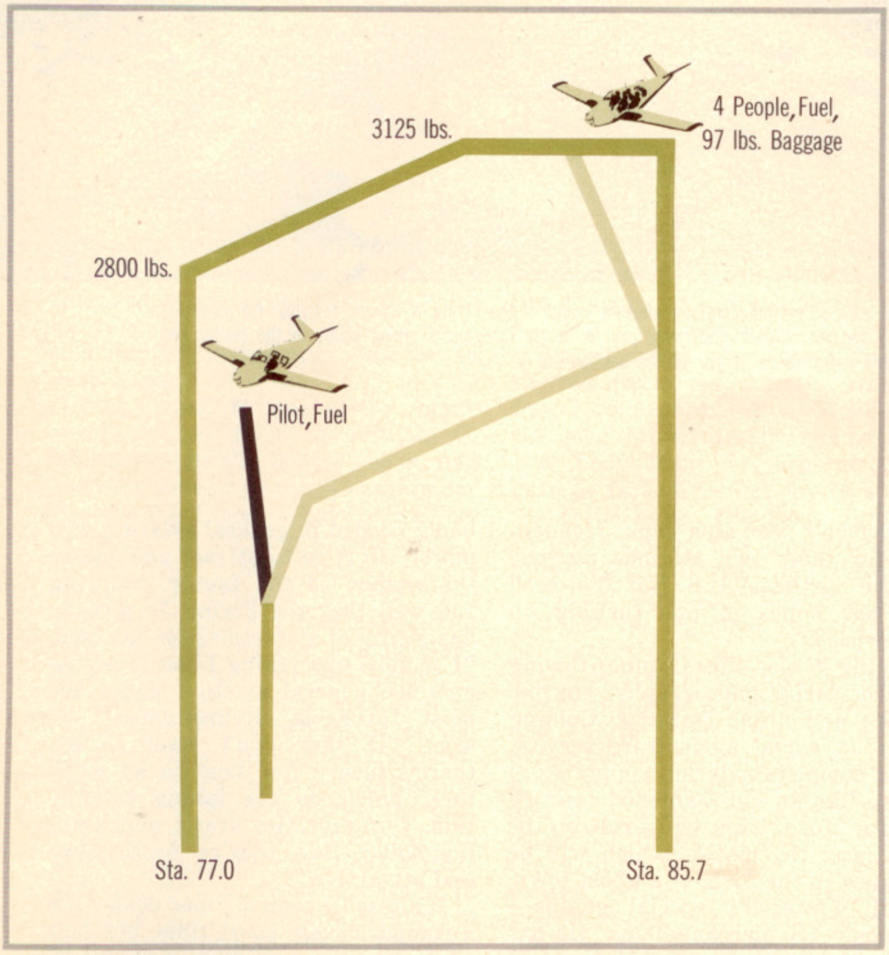
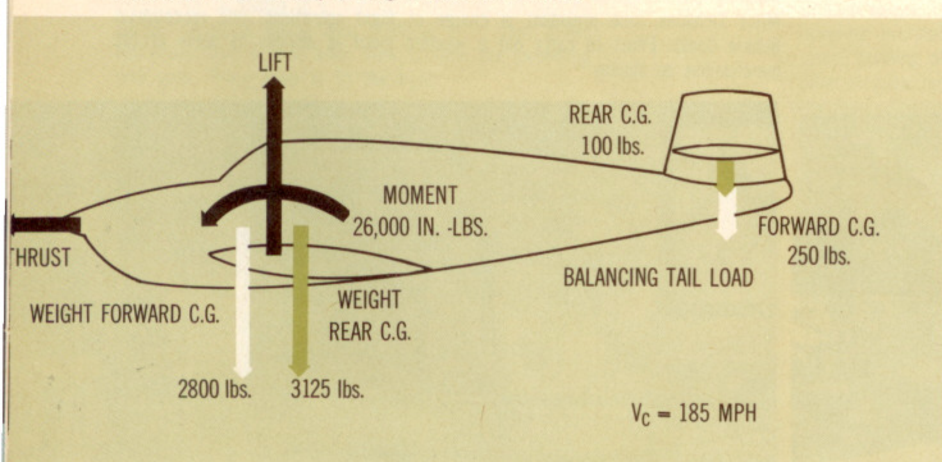


FIGURE 1 A useful guide in analyzing weight and balance of an aircraft is shown in this diagram

FIGURE 2 Basic forces and moments experienced by an aircraft in level flight are illustrated in this cutaway drawing of Beechcraft Bonanza



by M. J. GORDON • AOPA 24227

The problem of weight and balance has been with us as long as airplanes have flown. Although this article deals with the basic features of balance, it is necessary to consider both weight and balance. There has been considerable misunderstanding over the years about the effects of cg (center of gravity) on the airplane's characteristics.

If airplanes were always flown within the design cg envelope, the overall safety record probably would be better. Therefore, my primary objective is to point out how the cg limits were established and what physical factors helped determine these limits. This should give the pilot a better understanding of how the design of the airplane was reached. It is my hope that this knowledge will make it possible for the pilot to operate his airplane more safely, get more utility out of it, and do so with greater peace of mind.

The subject of weight and balance has been around so long that a number of misconceptions have been built up in the minds of pilots. I would like to "slay a few dragons," eliminate some old superstitions, and give a few practical suggestions on how to judge if your airplane is loaded within proper cg limits. Finally, a practical "do-it-yourself" weight and balance form is presented to assist the pilot in getting an accurate idea of whether his own airplane is loaded within the approved cg limits.

For convenience, the current weight and balance information from this year's Beechcraft P35 *Bonanza* is used as an example. The form shown in Figure 1 has been found useful in analyzing weight and balance of an airplane. Note that the chart shows the cg position of the airplane with 58 gallons of fuel in the main tank and pilot only. From this diagram it can be seen that the cg is at Station 77.4 and the gross weight is 2,520 pounds. The Station is the location of cg in the fuselage. It is merely the location in inches from some conventional reference line. It is sometimes located in reference to

Bother?

the wing. In this case it is called %MAC, or percent of mean aerodynamic chord.

Later on, it will be shown how this cg position and weight affect flight characteristics. The second point of most general interest is the gross weight point which is located at Station 84.5 and a gross weight of 3,125 pounds. This weight and cg condition is for a typical airplane loaded with pilot, copilot, two passengers, 97 pounds of baggage, and 58 gallons of fuel. These two conditions show rather graphically the normal range of cg that can be expected in a typical four-place airplane.

Figure 2 gives a good idea of the basic forces and moments (force times distance) involved on a *Bonanza* in level flight. This diagram is for level flight at 185 m.p.h. indicated airspeed. At forward cg, the down tail load is 250 pounds. On the same diagram is a rear cg condition at gross weight, which shows that the down balancing tail load is now only 100 pounds. It is easy to see that the extra lift which the wing must produce is more for the forward cg condition than it is for the aft cg condition.

It is common belief that an airplane loses considerable speed when the cg is located well aft. In practice, the difference in these numbers (150 pounds) in relation to the total gross weight of the airplane is about 5%. Therefore, there is little detrimental effect on the cruising speed at 65% power, but amounts to 3 m.p.h. at 50% power. It is interesting to see that there is a definite increase in total load that the wing must support at forward cg condition, for the same gross weight condition.

In Figure 3 a new *Bonanza* is loaded to forward cg and, from the way it sits on the ground, you can see roughly how it is loaded. You can see that the nose gear strut is compressed, that the nose gear tire is compressed, and that the airplane tends to sit in a fairly level attitude on the ground. If you walk up to the

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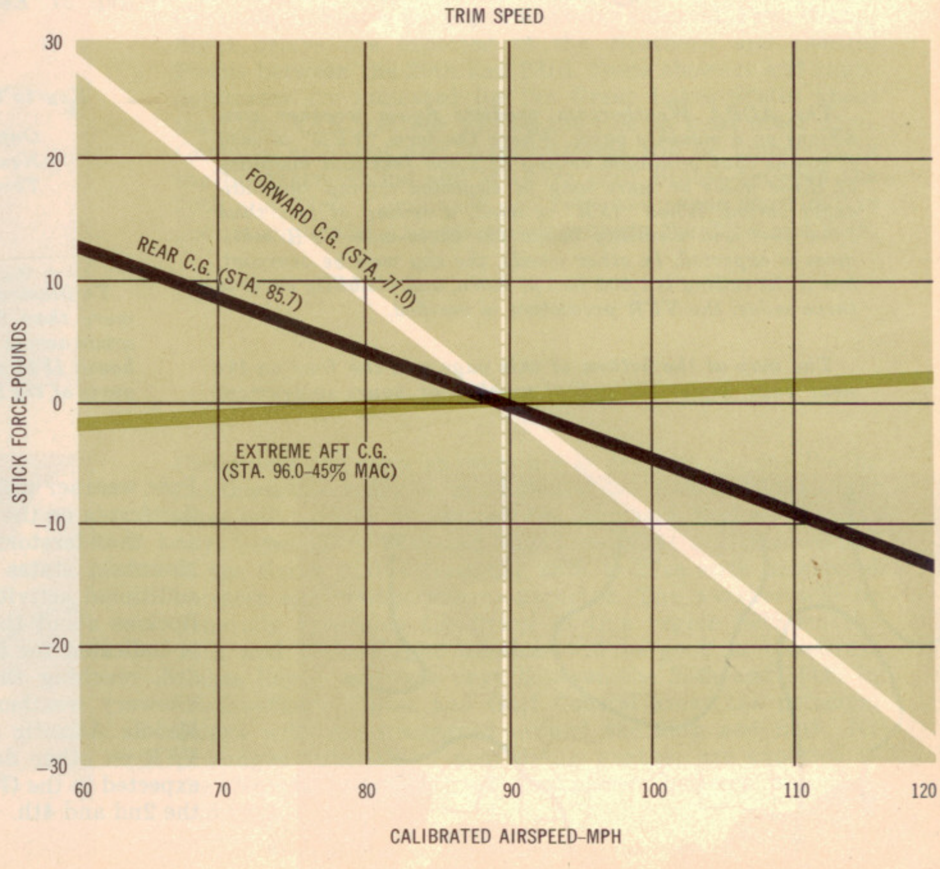
FIGURE 3 Note Bonanza's compressed nose gear strut, level attitude with ground when loaded to forward cg

FIGURE 4 Here, in rear cg condition, Bonanza shows weight thrown on main struts, nose gear strut is fully extended

FIGURE 5 This diagram illustrates the effect of cg on stick force landing configuration



Weight and Balance

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airplane and lean on the horizontal tail, you will find that it requires considerable effort to lighten the nose wheel.

In Figure 4 we have a *Bonanza* loaded on the ground in a typical rear cg condition. Here again, you will notice that the main struts and tires are deflected, the nose gear strut is extended more than the normal ground unloaded attitude, and the airplane sits on the ground at a higher angle. If a person leaned on the tail, it would be possible to lighten the nose gear without too great an effort.

As mentioned earlier, there seems to be a general view that performance is better when the airplane is loaded at forward cg. As a matter of fact, a good friend of mine made quite a point of explaining that even when he was by himself, he considered taking his suitcase out of the baggage compartment and putting it in the front seat to get the best possible performance out of the airplane. Recently we took a new *Bonanza*, loaded it to Station 80.4 at 3,000 pounds and made a flight test of the cruising speed for a range of power settings. We then reloaded the airplane to the same gross weight to a cg of 85.7 inches and 3,000 pounds. Test points indicated no appreciable difference between the two conditions except at lower speeds, where rear cg is better. During World War II this false impression reached such magnitude that the military found it necessary to run actual flight tests on a number of bombers in order to prove that cg was not an important factor for long-range cruise.

Perhaps one of the most important effects of cg position on airplane characteristics is the change in longitudinal stability. In Figure 5 we have plotted the change in stick force with change in air speed for two different cg positions. From this diagram it is obvious that the stick force—that is, the force which the pilot feels as he changes from a given trim speed—varies greatly with cg position. In the case illustrated, which is for power-off landing configuration, the stability at forward cg is approximately twice as great as it is for rear cg.

From a practical standpoint this is important, because it gives the pilot warning of a change in speed. From an FAA standpoint, it is necessary that a change in force be clearly perceptible to the pilot with a change in air speed. As the cg goes further and further aft, this change of force becomes less and less. In an extreme aft cg, it is possible that the force will go to zero, then actually reverse. Stick travel will do the same thing. In this extreme aft cg condition, it would be necessary for the pilot to push for takeoff and push to make a normal landing. Naturally, this required change in forces would be confusing and dangerous. This condition would be easier to reach on some airplanes than others.

We have loaded airplanes experimentally far enough aft to demonstrate this adverse situation. All Beech airplanes are approved at an aft cg that is well forward of this reversal point. However, in practice, it would be possible to load our airplane, as well as most other commonly used airplanes, far enough aft that the stick force characteristics could be very unpleasant. An airplane loaded with extremely heavy cargo in the baggage compartment, with no consideration given to the approved limit, would require a high degree of skill by the pilot for takeoff and landing. In good weather under good conditions, an experienced pilot might get away with this. However, add turbulent air and short fields, perhaps at night or in instrument weather, and the combination becomes extremely critical.

One normal reaction would be, "Why not just design the airplane with the cg

M. J. Gordon

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More than 24 years as an aeronautical engineer gives M. J. "Jerry" Gordon (AOPA 24227) an authoritative position on which to base the information he discloses in this article. Following graduation from New York University in 1938, Gordon worked for several eastern aircraft companies until 1940, when he joined Beech Aircraft as chief of aerodynamics. That firm has made good use of the 46-year-old aeronautical engineer's talents ever since. In July 1960, he was advanced to the position of manager of commercial engineering. During his 22 years with Beechcraft he has intermittently taught night classes at the University of Wichita in aerodynamics and flight testing. He holds a commercial pilot license with single and multi-engine land and instrument ratings.

always so far forward that the extreme rear condition cannot be reached?" The practical limitation of such an approach is obvious: as the cg goes forward, the stick forces increase. It then becomes difficult to design a longitudinal control system so that the stick forces do not become uncomfortable or unreasonably high.

FAA requirements put a limit of 40 pounds on the effort required to reduce the speed from trim speed to 10% above stall. Also, from Figure 2 it can be seen that as the cg goes forward, the down load on the horizontal tail becomes progressively higher. As this down load increases, the load carried by the wing must increase, decreasing the total efficiency of the airplane. The structural loading on the wing increases and imposes a penalty on the weight of the structure.

Another interesting and important flight characteristic is the effect of cg on maneuvering stick forces. This is simply the situation where the pilot chooses to execute a banked turn out of level flight. A 60° bank imposes a 2g load on the airplane. For the two conditions we have chosen to study, at forward cg if the pilot chooses to perform a 60° bank out of level flight at a speed of 150 to 200 m.p.h., an additional force on the control column of 30 pounds will be required. At rear cg, a force of only 10 pounds is required to execute this same 60° bank.

This knowledge, recognized by the pilot, will give him a good indication of the flight attitudes and cg of his airplane from the feel of the controls. Under extreme conditions, a pilot who has been flying the airplane loaded to forward cg could get into trouble if he then flew the airplane loaded to rear cg without realizing that the same maneuver could be accomplished with one-third of the force. It is my opinion that these forces should be reasonably high so that the pilot has better feel and is less likely to overstress the airplane. We have made a concentrated effort to increase these maneuvering stick forces in our airplanes over the past few years. We feel this contributes to safety and therefore is a desirable characteristic.

The stall speed of the airplane is also affected by cg position. In general, the range of cg travel at gross weight is so small that the pilot is rarely aware that the stall speed varies with cg position. In Figure 6 stall speeds are plotted for the full range of cg positions on the *Bonanza*. Although it is not possible to load the airplane to gross weight at the forward limit, the curves have been extended to show this effect. Total change in stall speed is not great—only a matter of a couple of miles per hour. However, it does tend to illustrate that as the cg moves forward the down load on the tail increases. This makes it necessary for the wing to carry additional load. In the average pilot's experience, the airplane is at light weight at the forward cg condition, so the stalling speed appears to be less. This again leads to misconception as to the true effect of cg position.

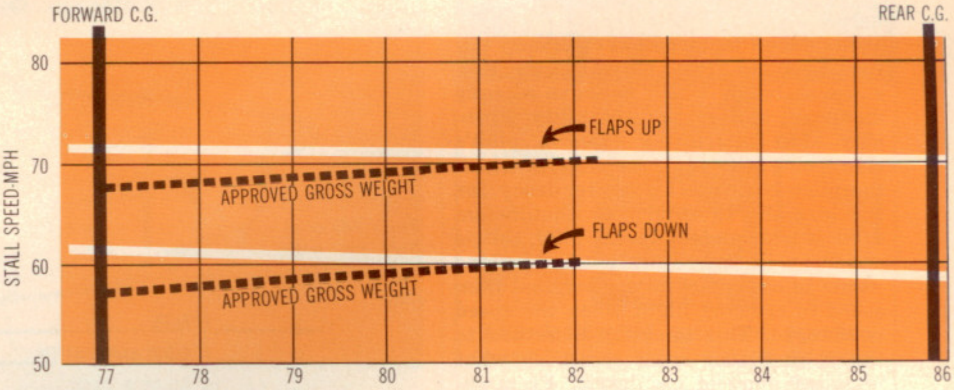


FIGURE 6 With an aircraft gross weight of 3,125 pounds, this drawing shows the effect of cg on stalling speed, power off

Ability to trim the airplane in a hands-off landing glide is usually a critical design characteristic. Flight tests are conducted to determine the most forward cg position at which it is possible to trim at a speed of 1.5 times the stall speed in a power off glide. This requirement generally limits the most forward cg at which we are able to meet FAA requirements. From a pilot's standpoint this is very apparent. In the forward cg condition on most four-place airplanes, it is not possible to reduce the elevator forces to zero for landing, even with all elevator trim power wound in. At rear cg it is possible to increase the tab setting to where elevator forces in landing can be reduced pretty much to zero.

This is another good indication to the pilot as to the location of the airplane cg. Where the trim speed in a glide is high, or when the forces required to land are high, he knows that he is loaded well forward.

In cruise flight the ease with which the airplane can be trimmed is directly related to the cg position. When the airplane is loaded well forward, the tab is less sensitive and easier to set for any desired flight condition.

The pilot will also be made aware of cg position by the characteristics of the elevator. At forward cg he will find that it takes more force and more travel for landing. On many four-place airplanes it is difficult, if not impossible, to stall the airplane when it is loaded forward. At rear cg the elevator becomes much more sensitive and requires much less travel, because more than enough elevator power is available to stall the airplane. This is shown in our diagram of basic forces and moments in Figure 2, where the down load required on the tail is much greater, requiring much more elevator travel.

In addition to changes in elevator power, there is a difference in the position that the elevator assumes in flight. In cruise flight at forward cg the elevator tends to trail up. As the cg is moved aft, the elevator angle tends to decrease and could actually, in an extreme case, assume a position below neutral. In the late 1940's, after Part 3 of the current Civil Air Regulations went into effect, trim requirements were very severe. Many four-place airplanes were designed which had difficulty in meeting trim requirements in a glide. It was found that by installing the stabilizer at a negative angle it was easier to provide sufficient up-elevator (down tab) to meet the trim requirements in glide. For this reason many of the early postwar airplanes, including the early *Bonanzas*, had the elevator down anywhere from 4° to 8° in cruise flight. Later, FAA trim requirements were relaxed and this down angle has been eliminated.

Airplane longitudinal stability is comprised of two major elements—static stability, which we have already discussed, and dynamic stability. Probably most interesting from a pilot's standpoint is dynamic stability, of which the pilot is aware by the tendency for the airplane to return to equilibrium after it is displaced. To the pilot, this is apparent in how quickly the airplane wants to come back to the original trim speed in cruising flight when the speed is changed. This tendency to return to the original trim speed results in what is called phugoid oscillation. From inside the airplane it is nothing more than how many trips on a roller coaster are necessary to return to the original attitude and air speed. In the general case, as the cg moves forward the airplane's tendency to return to its original trim speed becomes more positive.

Airplanes can be stable, neutrally stable, or unstable. Some well known airplanes will not tend to return to their trim speed when displaced or unstable, especially at rear cg. For example, if the speed is reduced 20% from cruise flight and the controls released, the airplane will continue to slow down until it approaches a stall. Conversely, if the speed is increased 20%, the speed will continue to increase until the red line is reached. This is an extreme case that would occur on most airplanes only if the airplane were loaded far beyond the approved rear cg limit. Although there is no FAA requirement on dynamic longitudinal stability, most four-place airplanes will not diverge at a rate fast enough to be of any concern to the pilot.

The period for one cycle is usually long—approximately 20 to 30 seconds—therefore the pilot has ample time to initiate recovery. This characteristic of an airplane, if known by the pilot, gives him another clue as to how his airplane is loaded.

The cg condition also has a marked effect on spin characteristics. For a typical four-place airplane, spin characteristics are conspicuously better at forward cg than they are at rear cg. As a matter of fact, it is often difficult if not impossible to spin an airplane at forward cg, whereas the same airplane at rear cg can be spun easily. The cg position affects altitude lost in a turn, the attitude which the airplane tends to assume in a spin, and the rate of recovery or number of turns required once recovery is initiated. It is not uncommon to require twice as much time for recovery at rear cg as at forward cg. For some designs of four-place airplanes, spin recovery at rear cg is the limiting factor as to how far back the airplane cg can be approved.

In addition to aerodynamic characteristics, there are a number of important structural characteristics affected by cg position. Probably the most conspicuous of these is that when the weight is located forward the nose wheel loads are increased. It is considered good practice to use a little more care in ground maneuvering at forward cg to keep from overloading the nose gear. Sometimes it is desirable to hold the wheel back to provide an aerodynamic relieving moment on the nose gear. The forward fuselage loads are increased by forward fuselage and the nose gear. Tail loads are also increased, which affects not only the horizontal tail, but the aft fuselage.

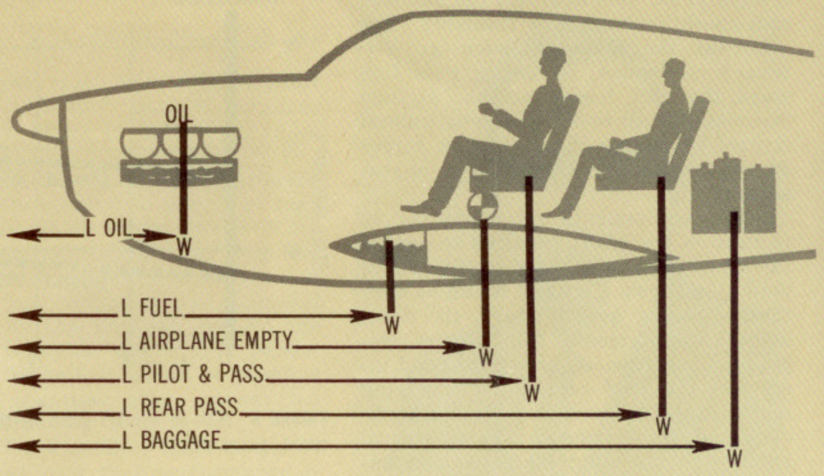
All manufacturers supply weight and balance data with their aircraft. It would be useful for the pilot to study such data and become familiar with effects of loading on the cg of his particular aircraft. Also, he may have optional equipment installed which has not properly been entered in the weight and balance of the basic airplane.

Figure 7 shows a typical loading for a current Beechcraft *Bonanza*. Using this same procedure you may readily compute the weight and balance of your airplane for each condition in which you are interested. First, determine the distance of each load item from a reference line. This is shown in Figure 7 as L, or length of each of the load items. The weight and balance data supplied with your airplane will give this dimension. In engineering language it is known as an arm. This distance multiplied by the weight of the item produces a "moment"—force times distance. In this case it is the weight of the load item times the distance the item is from a reference line.

All these moments, including the empty airplane moment, are totaled. This total is divided by total weight of the same items to find the cg of the plane.

Many people share a view that a little knowledge can be a dangerous thing. In the case of weight and balance, however, a study of all the factors involved should enable the pilot to get greater utility out of his airplane—more safely and efficiently. END

$$\text{C.G. (IN INCHES)} = \frac{\text{TOTAL MOMENT}}{\text{TOTAL WEIGHT}} = \frac{263{,}952}{3125} = 84.4$$



ITEM	LENGTH - INCHES (ARM)		WEIGHT - LBS.		MOMENT IN. - LB.
OIL	26	X	19	=	494
FUEL	75	X	348	=	26,100
AIRPLANE BASIC EMPTY WEIGHT	77.6	X	1981	=	153,738
PILOT	85	X	170	=	14,450
FRONT PASSENGER	85	X	170	=	14,450
REAR PASSENGERS	121	X	340	=	41,140
BAGGAGE	140	X	97	=	13,580
	TOTAL		3125		263,952

FIGURE 7 Typical loading for Beechcraft Bonanza. L indicates the distance of each load item from a reference line. From this example you may compute the weight and balance of your airplane

Forced Landing

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the ground, I knew we were going too fast so I reached for the brakes and couldn't find anything to get my feet on. Then I remembered that Duffy had them, so I yelled at him. After two or three tries, I managed to rouse him enough to get him to stop the ship. We were about 15 feet from the biggest road culvert I have ever seen. I crawled out of the cockpit after cutting the switch. A minute or two later I started to shake all over. The fear that I hadn't had time to feel had caught up with me. Duffy wasn't in any better shape. When the gas station attendant from across the road came running up with his fire extinguisher, he found two very sick sad sacks standing by a very sick airplane!

After we recovered, we returned the T-Craft to the field. For a long while the mechanic there couldn't find anything wrong. The motor seemed to run perfectly; he couldn't even get it to act up at full throttle. I'm sure the mechanic thought we had misused the plane somehow, but we were insistent so he kept looking. The ignition was checked but nothing was found. After about an hour's work, he decided to check the gas line. This action hit the jackpot. *It was full of leaves.* That's right, common ordinary tree leaves. I'd heard of all kinds of things forcing down airplanes but not leaves. After draining the gas tank and removing it, the mechanic discovered that the filtering screen inside the tank had come loose and, during all the years of standing outside, somehow or other leaves had gotten into the tank and down into the gas line. At full throttle there was enough pull to close off the flow of gas. END

THE AUTHOR

Donald L. Hauck, author of "Forced Landing," has been flying since 1945 (when he was a high school sophomore) and has owned all or part of five different airplanes since then. He presently owns a Cessna 140 and flies it whenever his duties as manager of a department store at Madison, Minn., permit. A graduate of the University of Minnesota, Hauck is now 32 years of age. He is married and the father of three children.