

The REAL Weight and Balance Box

Why There Are Limits

King Povenmire DPE

Often the most troubling limitation for our airplane involves how much can we put in it, and where should we put it. Manufacturers often build airplanes which have room for six people, 300 lb of luggage and 136 gallons of fuel with a useful load of 1000lb. Unfortunately with full fuel, there is weight allowance for one small person and an overnight bag, and with six people you could carry enough fuel to do the run-up. This invites owners to fudge a little to fully utilize their airplane.

In deference to Jessica Rabbit*, we have to ask "Why is the weight and balance box drawn that way?" What are the real reasons that weight and balance limits are set where they are? What are the consequences if we decide to carry just a bit more weight, or to place the load just a little outside the fore or aft limits of the box? Let's look at the reason behind each of these limits.

** The signature line of Roger's sultry cartoon wife in "Who Framed Roger Rabbit" 1981, Touchstone. "I'm not bad. I was just drawn that way."*

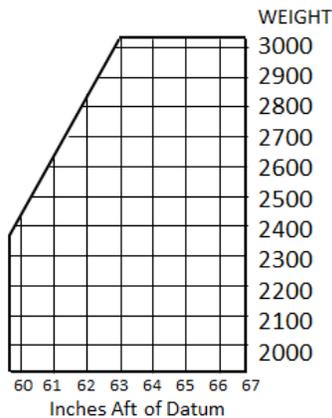


Figure 1. Typical Center of Gravity Limitation Diagram

Why can't we exceed the gross weight limit?

Well, of course we can, but not legally. All performance charts are developed at the most adverse corner of the weight and balance box. The most obvious weight limitation involves stresses imposed by turbulence or maneuvering, which multiply the weight by the acceleration force. That 20-pound overload becomes almost 90-pounds at the utility category G-load limit.

The G-load limit is normally 3.8-G for Normal Category and 4.4-G for Utility Category. This is not necessarily based on exceeding weight of the Useful Load items, but may be based on the failure of the battery box or some other installed item. The G-load limits are protected by a 50-percent margin. If you pull 3.9-G you won't pull the wings off, but non-critical structures may

begin to fail. Rivets may pop, the battery box may become deformed, or the hat rack may fail. The wing may come off at 5.7-G.

Maximum allowable weight frames the reference for performance data. If we exceed that weight we cannot guess what our performance might be. This is obvious if we consider extrapolating takeoff and climb data. At some weight, we will have to taxi to our destination.

Why is there a "Maximum Landing Weight (MLW)?"

Landing weight is set at the design load limit on the landing gear based on a hard landing. Landing speeds are also based on performance at that weight. If you land over the MLW you must do so very gently, and at a calculably higher speed.

Why is the forward limit drawn that way?

The forward limit is initially based on the weight-on-wheels stability on the ground. In addition, the elevator must be able to flare the aircraft for landing at the design landing speed. This second factor is responsible for the slanted line above a certain weight that moves the forward CG limit aft.

The slant of the line is based on several factors – primarily the maximum tail-down moment that can be supplied by the elevator at that speed. If you land with the CG forward of the slanted line, you must land faster.

Why not load slightly behind the aft limit?

This would be exceptionally handy in order to carry more luggage, or more fuel.** The aft limit is first placed where the aircraft will be stable in pitch during the full range of airspeeds and configurations. In essence the CG must be forward of the aerodynamic center of pressure in its most forward location in order to provide pitch stability. This concept will be explained later.

*** Most fuel is loaded aft of the aft limit. One notable exception is the popular Beechcraft Bonanza. In some models the fuel is well forward.*

The Center of Lift moves forward with increased angle of attack. The greatest angle of attack occurs near a stall. Therefore the most rearward CG must be fairly far forward on the wing.

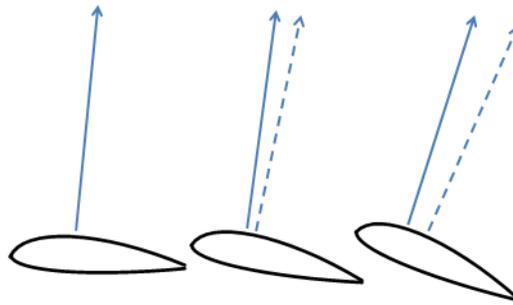


Figure 2. Center of Lift Movement with increased Angle of Attack

With the CG forward of the Center of Lift, the weight must be balanced by a down force provided by the elevator. This creates pitch stability. If turbulence pushes the nose up, airspeed decreases over the elevator and the nose is lowered.

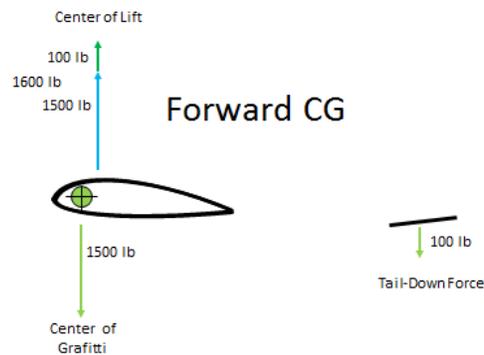


Figure 3. Forward CG requires more lift.

The additional down force produced by the tail must be lifted by the wing. The wing must lift both the gross weight and the tail-down force. At the forward limit, the airspeed is at its lowest and the angle of attack the highest. Stall speed is highest because the wing is closer to a stall at any given airspeed. Control pressures are heavier and the airplane is more stable.

When the CG is at the aft limit, the tail-down force is reduced. This means that the total weight to be lifted is reduced. Control pressures are very light, the airspeed is highest, but stability is reduced. Aerobatic aircraft are designed to be flown with the CG at the aft limit, making them almost neutrally stable so they maneuver easily.

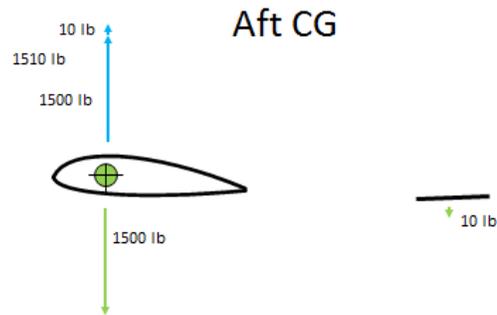


Figure 4. Aft CG requires less lift but provides less stability.

What if we want to go really fast? If we get some negative lift from the tail, we will be lighter yet and have a faster airspeed for a given weight. Yes, but there will be a penalty. If the elevator is required to produce positive lift, the whole thing becomes statically unstable. If the nose is pushed up by turbulence, the airspeed over the tail decreases, and the UP force decreases – causing the nose to rise farther.

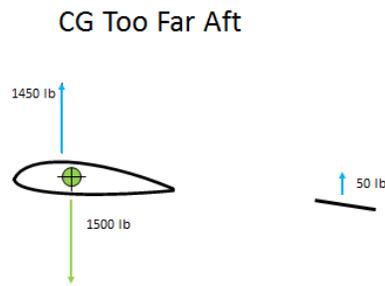


Figure 5. Provides negative static stability

So the aft CG limit can be no farther aft than the farthest forward position of the Center-of-Lift. But wait a minute. After takeoff we can move the Center-of-Lift farther aft by increasing speed as shown in the diagram below.

Reduced Angle of Attack Moves Center of Lift Aft

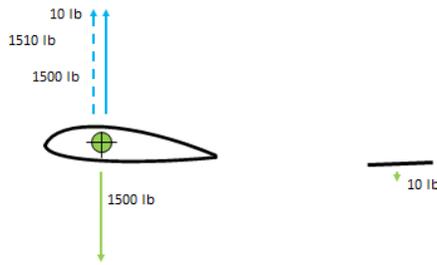


Figure 6. Flying faster regains stability

This little tidbit could save your bacon if you ever notice negative pitch stability right after takeoff. First you must control the oscillations - then you must add speed.

Why doesn't this problem happen more often? Many people load their single engine airplanes a little aft of the limit without losing control. True again. This brings us to the other consideration for placement of the aft CG limit – Spin Recovery.

Single engine airplanes must be able to recover from a one-turn spin with no more than one additional turn after recovery is initiated. Multiengine airplanes are exempt from this test. Therefore multiengine airplanes can be very sensitive to the aft-limit stability problem.

Presumably the manufacturers begin spin testing with the CG at the theoretical stability limit shown above. They must start the recovery after one complete 360-degree turn, and the recovery must be complete before another complete turn. If the airplane does not recover, they move the CG a little farther forward and try again.*** Therefore the manufacturer must usually move the aft CG limit forward of the stability limit.

*** Don't worry, they can use the same airplane. They recover by releasing birdshot from the tail cone and deploying a drag chute. The chute is then released for landing.

Let's use some real world scenarios to illustrate problems with two of these conditions.

Exceeding Forward CG

We had been using a particular airplane to perfect maximum performance Short Field Landings using the manufactures recommended approach speed. We were getting pretty good, but after a short layoff the highly competent student couldn't keep the nose-wheel off until the mains touched. After two tries I chose to demonstrate. I couldn't do it either. Before we started training, we had calculated that our CG was very close to the forward limit (the width of the pencil mark inside). After this flight we rechecked the CG. We found that during the week the

owner had installed a nine-pound auxiliary vacuum pump on the front of the firewall. We recalculated and found that our CG was one-pencil-width *forward* of the forward limit.

Exceeding Aft Limit

On this occasion we had loaded a light twin to the max gross weight and at the aft limit. Being polite, we estimated people's weights. After rotation, the airplane wanted to continue to pitch up. I made a control input, but now it wanted to pitch down. I felt like I was standing on top of a beach ball - gently pumping the yoke to counteract the negative static stability. Having learned the stability dynamics above, I stayed in ground effect and accelerated. I was relieved to feel the plane become more stable.

Now what? This airplane had a max landing weight that meant we would have to fly for about 90-minutes before landing. Where is the fuel? And where is the aft limit? I remembered the aft limit was at 89-inches and the fuel was at 93. We went safely to our destination gaining stability as we flew. The big guy didn't get to sit in back any more.

There have been several glider accidents in which the aft CG was exceeded. Witnesses say that the glider pitches up, then quickly down, then up higher. A wing drops and the glider crashes as the tow rope breaks. The glider pilot is usually killed.

Percent of Mean Aerodynamic Chord (MAC)

Many airliners present their CG data in terms of Percent MAC. The wing does not care where the CG is located relative to the datum. It must, however, be within a narrow range of locations relative to the Mean Aerodynamic Chord (MAC) of the wing. Airplanes using a common wing design will react similarly with the CG at the same Percentage of MAC.

To translate CG location from "Inches Aft of Datum" to "Percent MAC" we must find:

- MAC for a particular wing,
- location of the LEMAC (Leading Edge of the MAC)
- location of the TEMAC (Trailing Edge of the MAC) in terms of inches aft of datum.

This is very simple with a simple wing shape, but it gets complex with compound wing shapes found in swept wing jets.

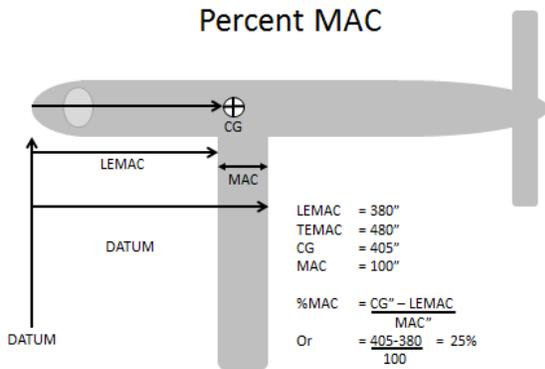


Figure 7. MAC of a simple wing

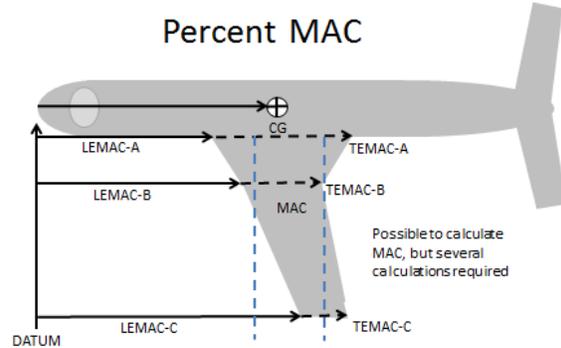


Figure 8. MAC of a more complex wing

The allowable Center of Gravity range on most aircraft varies from 12-15% for the forward limit to 30-32% for the aft limit. This nominal range of approximately 15% MAC shows us how small the actual range is on most airplanes.

Actual vs. Depicted Weight and Balance Limits

Many training diagrams show the CG range as from well ahead of the LEMAC to well aft of the TEMAC. When technical people send their diagrams to the artist, something often gets lost in translation. The actual weight and balance limits represent a small fraction of the chord of the wing. It is important to realize that the actual limits are smaller than depicted in training materials.

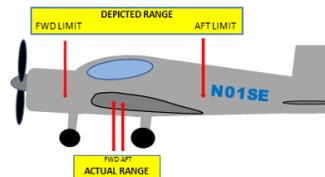


Figure 9. Actual vs. Depicted CG Range

As we can see, it is important to stay within the weight and balance limits of your aircraft. You may risk overstressing your aircraft in turbulence or during high G-load maneuvering. A few popped rivets on successive flights may decrease the structural integrity. An overloaded aircraft will not give the performance you have come to expect. In other cases exceeding the balance limits may drastically change the stability or stall/spin recovery capability.

**The important thing to take away from all this is
 WAIT AND BALANCE.**