Sport Aviation Specialties
2707 NW Cedar Brook, Lee's Summit, MO 64081, 816-838-6235, www.sportaviationspecialties.com

# WEIGHT & BALANCE FOR ELSA

In certificating light-sport aircraft and conducting ELSA repairman courses, I have found weight and balance to be confusing to ELSA owners getting ready for their DAR/FAA certification inspection. This article lays out the basics of the subject in a way that will hopefully clear up the confusion.

By the way, here we will discuss only fixed-wing ELSA. For weight-shift aircraft and powered parachutes, the fore/aft location of the cart or trike center of gravity (CG) is much less critical than for fixed-wing aircraft. In recognition of that fact, FAA has adopted the term "weight and loading" for trikes and PPCs.

## Two Kinds of Weight & Balance

Before we start talking technical details, I want to clear up one source of confusion I have noticed among my students: mechanics and pilots use the term "weight and balance" in two different ways. To a mechanic (or the owner of an ELSA preparing for a certification inspection), weight and balance means the act of actually weighing the aircraft to determine its empty weight and CG. It can also mean calculating a new empty weight and CG when equipment is added or removed. The mechanic or aircraft owner then produces a weight and balance report for the aircraft records.

To a pilot, weight and balance means starting with the empty weight and balance report and adding items of useful load (people, fuel, baggage, etc.) to determine that the loaded weight and center of gravity are within the allowable limits before any given flight—an FAA requirement.

Part of this confusion is because some ultralight manufacturers instruct owners to weigh the aircraft with a pilot in the seat and fuel in the tanks. In this article, we will discuss weight and balance from the mechanic's point of view, showing you how to create a conventional empty weight and balance report.

## Why Is It Important?

The "weight" part is important because higher loaded weight causes:

- Higher forces applied to the wings in flight and during maneuvers
- Higher forces applied to the landing gear and other parts of the aircraft during landing
- Longer takeoff and landing distances
- Slower climb rates

The "balance" part is important because loaded CGs aft of a certain point adversely affect:

- Longitudinal stability—the ability of the aircraft to return to its original flight path of its own accord, without pilot intervention, following a change in pitch attitude.
- Stall/spin characteristics—when the aft-CG airplane stalls, the spin is more likely to "go flat," where the nose of the airplane rises and the controls become ineffective, thus making the spin unrecoverable.

Additionally, CG locations too far forward may affect the ability of the aircraft to rotate for takeoff or flare for landing.

Aircraft designers specify a maximum weight and CG range, determined through a combination of engineering calculations, load testing, and flight testing, within which the aircraft can be safely operated. The FAA inspector or designated airworthiness representative (DAR) who inspects your aircraft for certification will require that you have

- Physically weighed the aircraft
- Calculated the empty weight and center of gravity
- Calculated the most-forward and most-aft CG locations to be expected, and

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- Prepared an accurate weight and balance report to include in the aircraft records.

## Some Basic Physics and Terminology

Before we get into the details, let's talk about leverage, which is simply a force applied at the end of a lever arm that causes the lever to rotate around a pivot point. Remember when you were a kid on the teeter-totter?

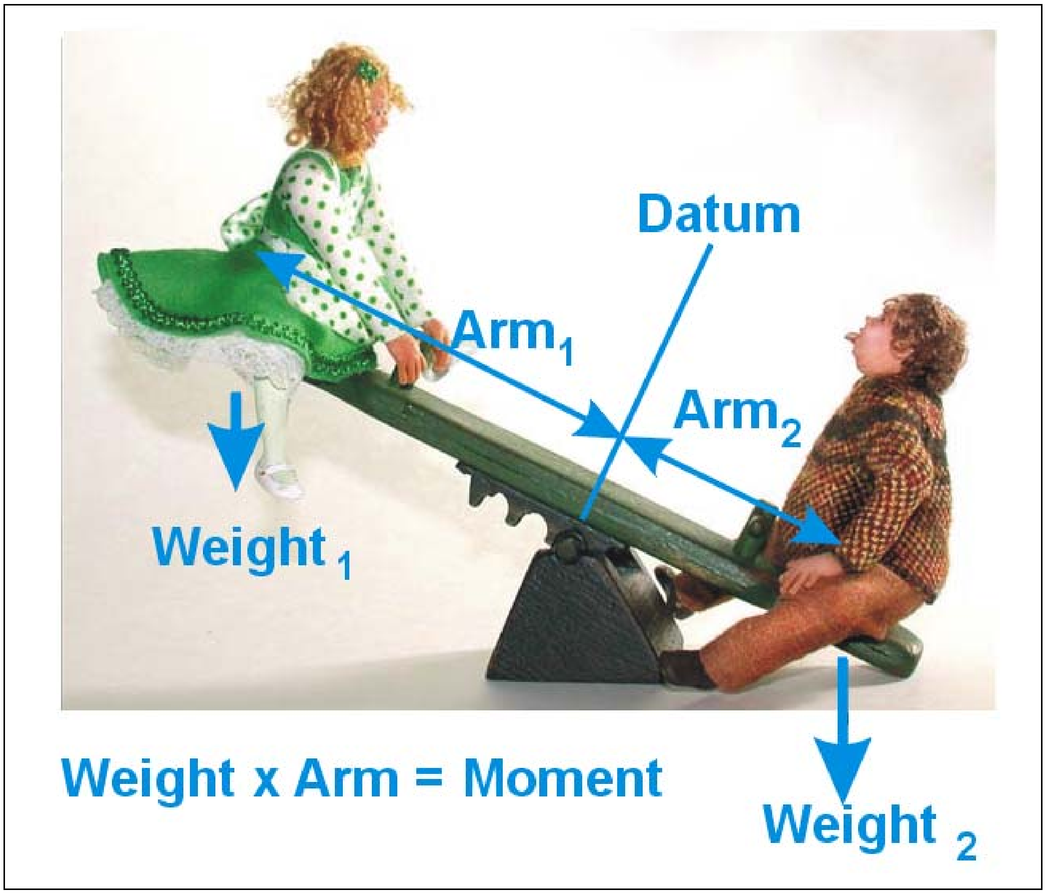


**Figure 1- Teeter-Totter**

As shown in Figure 1, if the person on the other end weighed less than you, you would have to scoot further toward the pivot for it to balance. This is an example of leverage. For balance to occur, your partner's weight multiplied by his distance from the pivot must be the same as your weight multiplied by your distance. Because you weigh more, your distance must be shorter. The concept of a force multiplied by a distance is key to understanding and performing weight and balance. In aviation parlance, the distance is referred to as an *arm* and the product of the weight times the arm is called a *moment*. Typically for small U.S.-registered airplanes, weights are expressed in pounds, arms in inches, and moments in inch-pounds.

So, if you were to set your aircraft on three scales—one for each wheel—you could read the weight on each wheel. Then, if you knew the arm measurement for each wheel, you could multiply the weight times the arm and get the moment for each wheel. If you added all three weights and all three moments, then divided the total moment by the total weight, the result would be the arm (better known as the CG location) for the airplane. That is basically all there is to weight and balance.

But where does one obtain the arm measurements? Another term you'll need to become familiar with is *datum*, which is simply a point on the aircraft's longitudinal axis from which all arms are measured.

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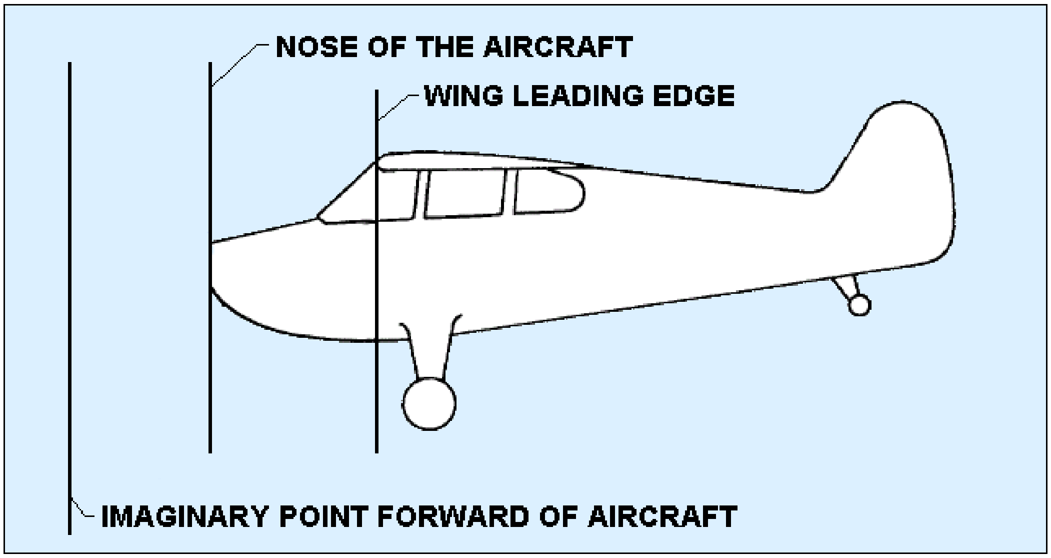


**Figure 2- Datum Locations**

Although it may not seem obvious, it does not matter where the datum is located, as long as the acceptable *CG range* is also defined relative to the datum. The datum is sometimes located at the wing leading edge, or perhaps the most forward portion of the aircraft. However, locating the datum at some imaginary point in space forward of the aircraft (say, 100 inches forward of the wing leading edge) makes the calculations easier. That is because arm measurements aft of the datum are considered positive (+) numbers and those forward of the datum are considered negative (-); by locating the datum well forward of the nose of the aircraft, all arms will be positive, thus eliminating the necessity to multiply, add, and subtract negative numbers.

Through a century of accumulated experience, it has been found that, for conventional wing-forward/tail-aft airplanes, the most forward CG limit will generally be located at 20-25% of the wing chord and the most aft CG limit at 30-40% of the wing chord.

So, if your airplane had an acceptable CG range of 25-35% chord and your wing chord measured 60 inches, that would mean your acceptable CG range would be 15-21 inches aft of the wing leading edge. And, if the designer had chosen a datum 100 inches forward of the wing leading edge, the CG range would be 115-121 inches aft of the datum. Simple, huh?

If the airplane has a swept or tapered wing, the designer may reference the acceptable CG range to a *mean aerodynamic chord* (MAC), which is the mathematical equivalent to a constant-chord wing.

## Down to the Nitty Gritty

Now, with that grounding, let's do a sample weight and balance. For this exercise, assume you own a Challenger II powered by a 52-hp Rotax 503. Figure 3 shows a side view of the aircraft with all the manufacturer-supplied weight and balance specifications (note that we are using the Quad City specified maximum weight of 800 lbs; in some cases they are now allowing an increase to 1000 lbs).

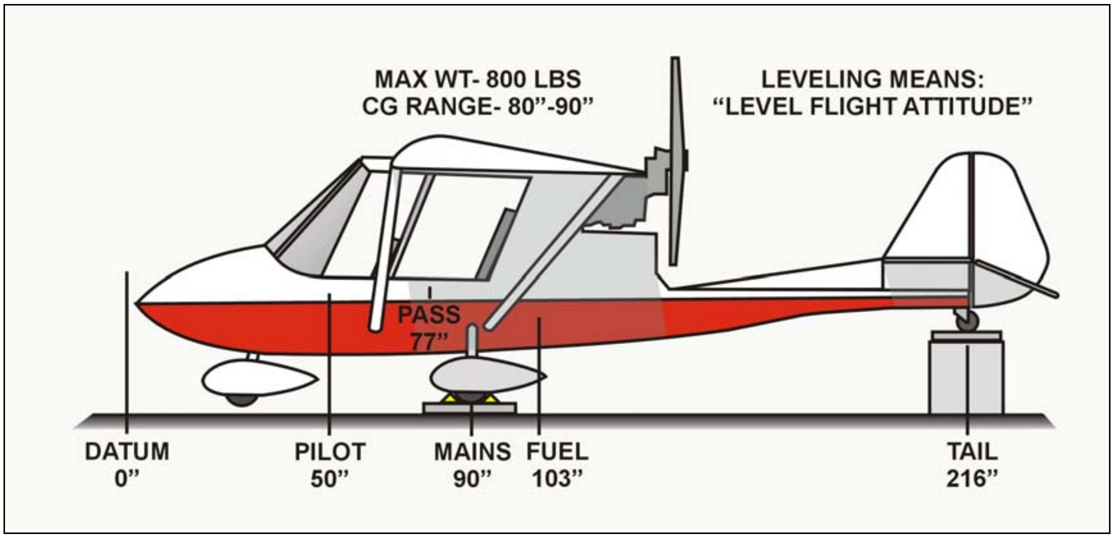


**Figure 3- Challenger II Weight & Balance Specifications**

Before we actually weigh the airplane, we need to perform some preparatory steps:

- Clean the aircraft. Accumulated dirt and moisture has weight.
- Make certain there is no accumulated water or ice anywhere in the aircraft.
- Perform the weight and balance in a closed building with a flat, relatively level floor. Stray air currents may affect the scale readings.
- Assure that all items of required equipment are in the aircraft.
- Assure that no other items (headsets, knee boards, etc) are in the aircraft.
- Drain the fuel tanks.
- Assure that, if installed, the oil reservoir and coolant system are full.
- If at all possible, use three scales. While it is feasible to use one scale and move it from wheel to wheel, the possibility of errors is greater.
- Check the calibration of your scales. If you are using un-calibrated scales (such as bathroom scales), weigh a known-weight heavy object and a known-weight light object on each scale, noting the errors at both ends of the range. A convenient heavy object could be your own weight, if known accurately. A convenient light object might be a number of one-gallon plastic jugs filled with water—8.33 pounds per gallon.
- Initiate your weight and balance report form. You may use one supplied by the manufacturer, one you made up, or one from another source. We created the one shown in Figure 4 as an Excel spreadsheet to simplify the calculations.

  As with any other piece of paper you generate for your aircraft records, be sure to list the date, the N-number, the builder/model/serial number data, and your name and signature. The report form should also list datum location, leveling means, total fuel capacity, baggage allowance, maximum weight, and the allowable CG range. It is also a good idea to list where the information came from, i.e., from the manufacturer or determined by the person performing the weight & balance.

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| AIRCRAFT WEIGHT & BALANCE REPORT- ACTUAL WEIGHT | | | |
|---|---|---|---|
| Date: | 12/15/2006 | | |
| Registration No: | N555RC | | |
| Manuf/Builder: | QUAD CITY | | |
| Model: | CHALLENGER II | | |
| Serial No. | CH55555W5555 | | |
| Performed By: | JOHN J. SMITH John J. Smith | | |
| | | Determined From: | |
| | | Manuf Data | My Data |
| Datum Location: | 90" FWD OF MAIN WHEELS | X | |
| Leveling Means: | "LEVEL FLIGHT ATTITUDE" | X | |
| Total Fuel Capacity: | 10 GALLONS (60 LBS) | X | |
| Max Gross Weight: | 800 | X | |
| CG Range: | 80-90 " AFT OF DATUM | X | |

| Empty Weight & CG | Weighing Point | Weight (lbs) | Arm (in) | Moment (in-lbs) | Center of Gravity (in) |
|---|---|---|---|---|---|
| Left main wheel | Scale reading: | 183 | | | |
| | Tare: | 2 | | | |
| | Net weight: | 181 | 90 | 16290 | |
| Right main wheel | Scale reading: | 185 | | | |
| | Tare: | 5 | | | |
| | Net weight: | 180 | 90 | 16200 | |
| Tailwheel or Nosewheel | Scale reading: | 58 | | | |
| | Tare: | 9 | | | |
| | Net weight: | 49 | 216 | 10584 | |
| | **Empty weight/CG:** | **410** | | **43074** | **105.06** |

| Most Aft Loading | Item | Weight (lbs) | Arm (in) | Moment (in-lbs) | Center of Gravity (in) |
|---|---|---|---|---|---|
| | Aircraft empty: | 410 | 105.06 | 43074 | |
| | Pilot: | 170 | 50 | 8500 | |
| | Passenger: | 0 | 77 | 0 | |
| | Baggage: N/A | | | 0 | |
| | Fuel: | 48 | 103 | 4944 | |
| | **Weight/CG** | **628** | | **56518** | **90.00** |

| Most Fwd Loading | Item | Weight (lbs) | Arm (in) | Moment (in-lbs) | Center of Gravity (in) |
|---|---|---|---|---|---|
| | Aircraft empty: | 410 | 105.06 | 43074 | |
| | Pilot: | 170 | 50 | 8500 | |
| | Passenger: | 170 | 77 | 13090 | |
| | Baggage: N/A | | | 0 | |
| | Fuel: | 26 | 103 | 2678 | |
| | **Weight/CG** | **776** | | **67342** | **86.78** |

| Flight Test Loading | Item | Weight (lbs) | Arm (in) | Moment (in-lbs) | Center of Gravity (in) |
|---|---|---|---|---|---|
| | Aircraft empty: | 410 | 105.06 | 43074 | |
| | Pilot: | 195 | 50 | 9750 | |
| | Passenger: | 0 | 77 | 0 | |
| | Baggage: N/A | | | 0 | |
| | Fuel: | 60 | 103 | 6180 | |
| | **Weight/CG** | **665** | | **59004** | **88.73** |

**Figure 4- Challenger II Actual Weight & Balance**

- Initiate an equipment list report form, which is simply a list of all the equipment installed in the aircraft at the time of the weight and balance. After all, without an equipment list, how would you (with your faulty memory) or the next owner know when equipment changes warranted a new weight and balance? Be sure to identify the equipment list in the same way as the weight and balance form. The equipment list we use is shown in Figure 5.

| EQUIPMENT LIST | | | | | |
|---|---|---|---|---|---|
| Date: | 12/15/2006 | | | | |
| Registration No: | N555RRC | | | | |
| Manuf/Builder: | QUAD CITY | | | | |
| Model: | CHALLENGER | | | | |
| Serial No. | CH55555W5555 | | | | |
| Performed By: | JOHN J. SMITH John J. Smith | | | | |
| **Item** | **Manuf** | **Model No.** | **Serial No.** | **Wt (lbs)** | **Arm (in)** |
| Engine | ROTAX | 503 DCDI | 4006221 | | |
| Propeller | WARP DRIVE | 60x42- 3BLADE | N/A | | |
| WHEELS | ORIG QUAD CITY | N/A | N/A | | |
| TIRES | ORIG QUAD CITY | N/A | N/A | | |
| BATTERY | MARATHON | 17 AMP-HR RG | N/A | | |
| ENG INF SYSTEM | GRAND RAPIDS | 2002 | N/A | | |
| NAV/STROBE LIGHTS | WHELEN | A-600-PR-14 | N/A | | |
| AIRSPEED INDICATOR | HALL | N/A | N/A | | |
| COMPASS | AUTOMOTIVE | N/A | N/A | | |
| BALLISTIC PARACHUTE | BRS | BRS-5 900 | 10198 | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |

**Figure 5- Challenger II Equipment List**

With that preparation, place the aircraft on the scales. Level the aircraft longitudinally and laterally using the leveling means specified by the manufacturer—in this case Quad City says only to place the Challenger II in a "level flight attitude." Although the Challenger II is a tricycle-gear airplane, with nobody in it, it rests on its tail. Therefore, you'll need a scale under the tail, with some sort of stand to bring the nose wheel down level with the mains.

Don't set the brakes—that can introduce side forces that may affect scale readings—instead, use wheel chocks.

Make note of each scale reading, then take the aircraft off the scales. Next, weigh the wheel chocks or stands used on each scale (known as the tare weights) and make note of the readings. Depending on how your weight and balance form is set up, you may need to subtract the tare weights before entering the data on the form. Our form allows entry of the total weight and the tare, and automatically calculates the net weight at each wheel, as shown in Figure 4.

Enter the arm for each scale location in the ARM column, then multiply the net scale weights times the arm and enter the result in the MOMENT column. Add all three net scale weights to get the total weight. Add all three moment figures to get the total moment. Then divide the total moment by the total weight to get the CG. Note: do not add the three individual figures in the ARM column.

Now you have determined the aircraft empty weight and CG.

## Most-Aft and Most Forward Loading Conditions

You'll also need to calculate the most-aft and most-forward loaded CG.

The FAA Aircraft Weight & Balance Handbook FAA-S-8083-1 describes the accepted method for calculating the most-aft and most-forward CG conditions. At the outset, we should acknowledge that, depending on the configuration of your airplane, using this method may not result in information that is particularly useful in planning a flight. However, we will explain it, since it is the accepted method. Here again, it would be a good idea for you to check with your FAA office or DAR beforehand—they may want you to use a different method.

The basic idea is to maximize or minimize useful load items whose arm locations fall outside the allowable CG limits. Thus, for the most-aft condition, you would maximize items that are located aft of the aft CG limit and minimize items forward of that limit. For the most-forward CG calculation, you would maximize items forward of the forward CG limit and minimize items aft of that limit. For both conditions, you must assure that the resulting loaded weights and CGs are within the aircraft maximum weight and CG range.

Note that, using the official FAA handbook method, if the useful load items are all within the allowable CG range (as would be the case for, say, a RANS S-6 Coyote), your most-aft and most-forward loading conditions may well be the same.

According to the FAA handbook, the pilot/passenger weight to be used for most-aft and most-forward calculations is 170 pounds, rather than the actual anticipated weight of the occupants.

Also, minimum fuel weight should be calculated using the FAA handbook formula: 1/12 gallon per maximum-except-take-off (METO) engine horsepower. Since gasoline weighs 6 pounds per gallons, an easy way to figure minimum fuel weight is to simply divide the engine horsepower by two. For example, the minimum fuel weight for 52-hp Rotax 503 would be 26 pounds or about 4.7 gallons. With some ultralights, this may seem like a lot of fuel, but it is the FAA-accepted way of calculating minimum fuel.

For our Challenger II, Figure 4 shows that the most aft CG worked out to include the pilot (which we always include), and no passenger. Note that, as instructed, we used the standard weight of 170 pounds for the pilot. Note also that, in order to keep the most-aft CG within the 80-to-90-inch range specified by the manufacturer, we can carry only 49 lbs of fuel, short of the 60-lb capacity.

The most-forward condition worked out to include only the pilot, a passenger, and the 26-lb minimum fuel as calculated using the standard formula explained above.

## Flight Test Loading Condition

Last but not least, your FAA inspector/DAR may want to see the actual loading you plan to use for your Phase I flight test. Here, as shown in Figure 4, we use the actual pilot weight rather than the FAA-standard 170-pound figure, along with the actual fuel loading we plan to use. Your operating limitations document requires that the pilot be the only occupant of the aircraft during Phase I flight testing, so no passenger weight is included.

## Paperwork

So now, you have completed the weight and balance report. At this point, you need to make an entry in your aircraft maintenance logbook similar to this:

> "12/15/2006 TT-306.5 Performed weight and balance by actually weighing the aircraft. See weight and balance report this date. Signed [your name]"

## Future Changes to Your Weight & Balance

What happens if you add or remove equipment—do you have to re-weigh the aircraft? The answer is that, if you know the accurate weight and arm of any piece of equipment added or removed, you can use the last weight and balance report to calculate a new weight and balance, without re-weighing the aircraft. Figure 6 shows a hypothetical example for our Challenger II, where we removed the ballistic parachute and added a GPS receiver.

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| AIRCRAFT WEIGHT & BALANCE REPORT- EQUIPMENT ADDITION/REMOVAL | | | |
|---|---|---|---|
| Date: | 1/12/2007 | | |
| Registration No: | N555RC | | |
| Manuf/Builder: | QUAD CITY | | |
| Model: | CHALLENGER II | | |
| Serial No. | CH5555W5555 | | |
| Performed By: | JOHN J. SMITH John J. Smith | | |
| | | Determined From: | |
| | | Manuf Data | My Data |
| Datum Location: | 90" FWD OF MAIN WHEELS | X | |
| Leveling Means: | "LEVEL FLIGHT ATTITUDE" | X | |
| Total Fuel Capacity: | 10 GALLONS (60 LBS) | X | |
| Max Gross Weight: | 800 | X | |
| CG Range: | 80-90" AFT OF DATUM | X | |

| Aircraft Empty | Item | Weight (lbs) | Arm (in) | Moment (in-lbs) | Center of Gravity (in) |
|---|---|---|---|---|---|
| | Old aircraft empty: | 410 | 105.06 | 43074 | |
| | Removed BRS-5 ballistic parachute | -23 | 85 | -1955 | |
| | Added Garmin 195 GPS | 2 | 24 | 48 | |
| | New Empty Weight/CG | **389** | | **41167** | **105.83** |

| Most Aft Loading | Item | Weight (lbs) | Arm (in) | Moment (in-lbs) | Center of Gravity (in) |
|---|---|---|---|---|---|
| | Aircraft empty: | 389 | 105.83 | 41167 | |
| | Pilot: | 170 | 50 | 8500 | |
| | Passenger: | 0 | 77 | 0 | |
| | Baggage: N/A | | | 0 | |
| | Fuel: | 49 | 103 | 5047 | |
| | **Weight/CG** | **608** | | **54714** | **89.99** |

| Most Fwd Loading | Item | Weight (lbs) | Arm (in) | Moment (in-lbs) | Center of Gravity (in) |
|---|---|---|---|---|---|
| | Aircraft empty: | 389 | 105.83 | 41167 | |
| | Pilot: | 170 | 50 | 8500 | |
| | Passenger: | 170 | 77 | 13090 | |
| | Baggage: N/A | | | 0 | |
| | Fuel: | 26 | 103 | 2678 | |
| | **Weight/CG** | **755** | | **65435** | **86.67** |

| Flight Test Loading | Item | Weight (lbs) | Arm (in) | Moment (in-lbs) | Center of Gravity (in) |
|---|---|---|---|---|---|
| | Aircraft empty: | 389 | 105.83 | 41167 | |
| | Pilot: | 195 | 50 | 9750 | |
| | Passenger: | 0 | 77 | 0 | |
| | Baggage: N/A | | | 0 | |
| | Fuel: | 60 | 103 | 6180 | |
| | **Weight/CG** | **644** | | **57097** | **88.66** |

**Figure 6- Challenger II Equipment Additions/Removals**

We start by entering the old aircraft empty weight/CG information and then listing each item of equipment added or removed. The weight for any item added will be listed as a positive number; the weight of any item removed will be negative. If we are using a datum located forward of the aircraft, all arm measurements will be positive numbers. Recalling high school algebra, if we multiply a negative number by a positive number, the result will be negative.

After calculating the new empty weight and CG, we need to recalculate the most-aft, most-forward, and flight test loadings and enter them on the form. This report then becomes the current weight and balance report for the aircraft records. Of course, you'll need to make another logbook entry similar to the one above documenting the new weight and balance. It is a good idea to keep the old report, but mark it as "***Superceded by new weight and balance dated xx/xx/xx.***"


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## Where to Keep Your Weight & Balance Report

Finally, where should you keep your weight and balance reports? In reality, there is no specific FAA regulation that requires you to carry it in the airplane on every flight. However, EAA recommends that you carry it in the aircraft, first making certain it is current and accurate. Without it, an FAA ramp check inspector might argue that you had violated CFR 91.13 (careless or reckless operation) or 91.103 (preflight familiarization).

For questions, comments, or a copy of our weight and balance spreadsheet, please email me at sportaviation@kc.rr.com.

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