

Weight and Balance



CIVIL AVIATION AUTHORITY
OF NEW ZEALAND
Te Mana Rererangi Tūmatanui o Aotearoa

Weight and Balance

Ever had that sinking feeling on takeoff,
when you thought that the aircraft
should be airborne by now?



CONTENTS

Weight	3
Balance	4
Weight and Balance for Aerobatic Aircraft	4
Definitions	5
Weight and Balance Calculation	6
Redistribution	9
What Units?	9
Conclusion	10



Ever wondered why the nose kept wanting to pitch up, despite trimming it all the way forward? Ever thrown passengers and bags into the aircraft in a hurry because you were running late, and then wondered why the aircraft over-rotated on takeoff and gave you a fright?

Well you shouldn't be wondering. You should have known that you were overloaded and that your centre of gravity (C of G) position was not within its range.

In all of these situations the aircraft may have got off the ground (eventually) and even flown satisfactorily, but you were tempting fate, and breaking the rules.

What would happen if one day you put more in the back locker than the aircraft could handle?

Weight

Manufacturers conduct extensive flight tests to establish loading limits for their aircraft because they are critical for safe flight. It is important that you adhere to these limits when loading your aircraft.



This Cessna 172 failed to clear trees at the end of the aerodrome. It was loaded with full fuel, four people and the baggage shown right.

Aircraft are designed to take a certain amount of G-load. Increasing the weight of the aircraft beyond the certificated limit reduces its capability to withstand G-load. This could result in structural failure, in a worst case scenario.

As far as performance is concerned, an overloaded aircraft will excel in only one area – rate of descent. This is not helpful when all you want to do is take off or climb.

A 'heavy' aircraft will have a:

- higher takeoff speed
- longer takeoff ground run
- reduced rate of climb
- reduced angle of climb
- lower ceiling
- shorter range
- reduced cruise speed
- increased stall speed
- higher landing speed
- longer landing roll.

The effects above show how the total performance of the aircraft is affected. These factors become crucial in the critical flight phases of takeoff and landing.



All of this equipment was stowed in the rear baggage compartment of the crashed aircraft (shown left).

Balance

It's not only the overloading of your aircraft that you need to be concerned about, but also the distribution of the weight. Your aircraft has C of G limits, and any loading that puts the C of G outside those limits will seriously impair your ability to control the aircraft.

If you load the aeroplane over its MAUW the C of G limits are totally invalid.

The more aft the C of G, the more unstable the aircraft. Forward pressure on the elevator control and full nose-down trim may be necessary to keep the aircraft from pitching up and stalling.

The need for increased forward pressure on the elevator control, and a tendency for the aircraft to take off in a dangerously nose-high attitude, are symptoms of an aft C of G. It is often characterised by light rearward elevator control forces, making the aircraft susceptible to inadvertent overstressing by the pilot.

The further aft the C of G is, the harder it is to recover from a stall. Conversely, a forward C of G needs backward pressure on the elevator control and nose-up trim. In addition to being very tiring, a forward C of G makes it difficult to rotate for takeoff and flare for landing – assuming that there was enough elevator control available to have become airborne in the first place. Incorrect loading can cause

the aircraft to be outside the C of G limits – even when it is within its gross weight limit. This condition can also be brought about during flight as fuel is burnt off. The aircraft might have been within limits on takeoff, but as fuel was used the C of G moved out of limits.

It is also very important to note that the rear (or forward) limit is not valid at anything over maximum weight. This means that if you load the aeroplane over its MAUW the C of G limits are totally invalid.

Weight and Balance for Aerobatic Aircraft

Both weight and balance are even more important for aircraft engaged in manoeuvring flight, such as aerobatics or spinning. Weights above maximum aerobatic weight are likely to overstress the aircraft. Operations outside the C of G limits can lead to loss of control. This is particularly acute for spinning. There have been fatal accidents in New Zealand caused when aircraft failed to recover from spins entered while the aircraft was outside the C of G limits.

Note that the limits for aerobatic flight are often more restrictive than those for normal operations in the same aircraft. A number of aircraft commonly used for aerobatic and spin training can not be flown for this purpose at regular weights – in particular, when flown dual, the fuel weight that can be safely carried is often very restricted.

Always check the weight and C of G limits for aircraft engaged in aerobatic flight.

Definitions

Centre of Gravity (C of G):

This is the point about which an aircraft would balance if suspended. Mathematically, it can be described as the pivotal point about which the nose-heavy and tail-heavy moments are of equal magnitude.

C of G limits:

These are the forward and aft points within which the C of G must fall if the aircraft is to operate normally and safely. These points are specified in the “Limitations” section of the Aircraft Flight Manual.

Datum:

An imaginary vertical line, specified by the designer, from which all horizontal C of G measurements are made. In most cases, the datum is located in the vicinity of the aircraft nose, usually the firewall.

Arm:

This is the horizontal distance from the datum to the C of G of the aircraft or to any item in it. A plus sign indicates measurement aft of the datum, a minus sign measurement forward of the datum. These values are found in the Aircraft Flight Manual and may be expressed in inches, centimetres or metres.

Moment:

The weight of an item multiplied by the arm of its position.

Empty weight:

The weight of an aircraft, including airframe, powerplant(s), all fixed equipment, full oil tank(s), and unusable fuel. The empty weight figure is found in the Form CAA2173 located in the Aircraft Flight Manual and can be expressed in pounds or kilograms. On the back of the form is listed all the equipment fitted at the time the aircraft was weighed.

Maximum all up weight (MAUW):

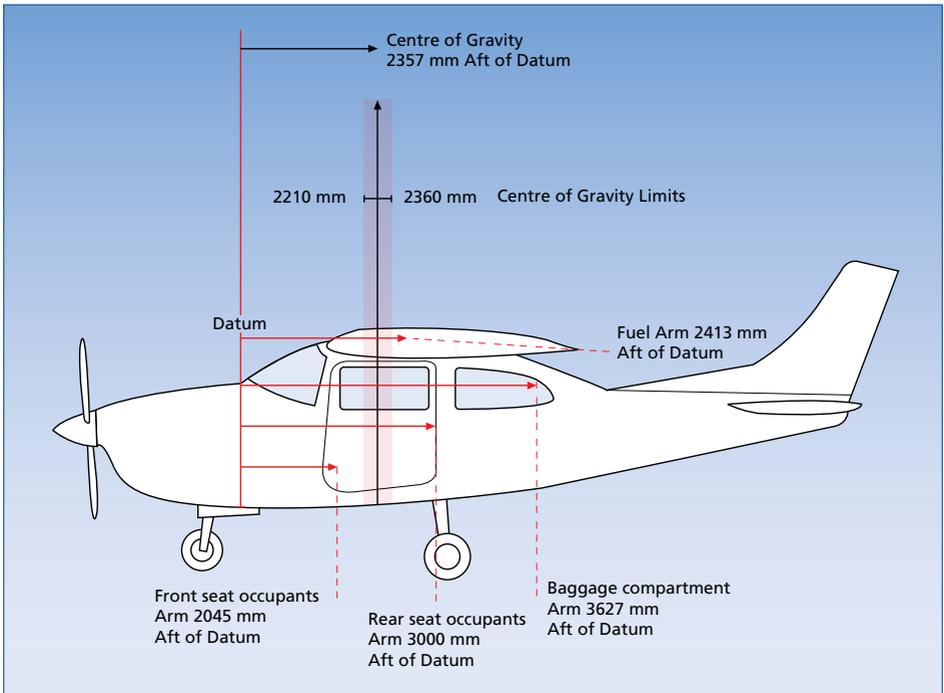
The maximum weight allowable for the aircraft. This value is given in the Aircraft Flight Manual “Limitations” section. Note that some aircraft have a higher permitted weight for takeoff than they do for landing.



The steps are as follows:

1. Insert Weight, Arm, and Moment for the aircraft empty weight in the appropriate columns.
2. Insert the Arms for fuel, front-seat occupants, rear-seat occupants and baggage compartment in the Arm column.
 - The only way to be sure of what passengers weigh is to put them on the scales.
3. Now fill in the Weight column gaps:
 - Total the Weight column. If it is greater than the MAUW, then you will need to leave something behind. Remove it from the aircraft, adjust the appropriate figure, and re-total the Weight column.
 - Now multiply each Weight by each Arm and insert the answer in the Moment column.
 - Total the Moment column.

Centre of Gravity



This illustrates the weight and balance calculation used in the example (left).

7. Divide the total Moment by the total Weight and that is your C of G position. Check that it is within limits. If not, you will need to redistribute your load.

There are other ways of working out the weight and balance, such as graphs that are provided in the Aircraft Flight Manual. They are good as a reference, but they are not as accurate as a weight and balance calculation like that shown.

Multi-Engine Example

For multi-engine aircraft, and some single-engine aircraft, working out whether you are under or over weight at all times during a flight is slightly more complicated than the previous example.

1. Take the empty weight of the aircraft and add the weight of occupants and baggage to be carried. This gives

the Zero Fuel Weight (ZFW) of the aircraft. Check this does not exceed the Maximum Zero Fuel Weight given in the Aircraft Flight Manual.

2. Add the fuel carried to the ZFW to give the Ramp Weight.
3. Subtract the run-up and taxi fuel from the Ramp Weight to give the Takeoff Weight. Check this does not exceed the Maximum Takeoff Weight.
4. Subtract the in-flight fuel burn to give the Landing Weight. Check this does not exceed the Maximum Landing Weight.

In many cases the Zero Fuel Weight is the limiting factor when loading multi-engine aircraft.

To calculate the C of G for multi-engine aircraft, follow the steps in the previous example.

Typical Weight Calculation for Multi-Engine Aircraft

Item	Weight	Limitations
Empty Weight of Aircraft	1418 kg	
+ Occupants	492 kg	
+ Baggage	80 kg	
= Zero Fuel Weight	1990 kg	Max. Zero Fuel Weight = 2000 kg
+ Fuel Carried	381 kg	
= Ramp Weight	2371 kg	
- Run Up and Taxi Fuel	10 kg	
= Takeoff Weight	2361 kg	Max. Takeoff Weight = 2361 kg
- Fuel Burn	250 kg	
= Landing Weight	2111 kg	Max. Landing Weight = 2245 kg

Redistribution

Imagine that you find the C of G is outside the aft (or forward) limit. Or maybe it's just within, but you want to move it closer to mid range so the aircraft handles better. The first option used by many is to move a couple of the heavier items forward (or aft) and then rework the weight and balance calculations, and this works well. If you would like to be more precise you can use the following formula:

$$\text{Distance weight shifted} = \frac{\text{Total weight} \times \text{Change of C of G}}{\text{Weight shifted}}$$

For example, say we have calculated our total weight to be 1055 kg, but we find the C of G needs to be moved forward 20 mm. We are able to move 25 kg of baggage items forward, and the distance this needs to be shifted is:

$$\begin{aligned} \text{Distance weight shifted} &= \frac{1055 \times 20}{25} \\ &= 844 \text{ mm} \end{aligned}$$

Alternatively, when the distance that can be moved is known, and we want to know how much weight to shift that distance, use this version of the formula:

$$\text{Weight shifted} = \frac{\text{Total weight} \times \text{Change of C of G}}{\text{Distance weight shifted}}$$

Using our previous example, but finding we are limited to shifting some baggage 700 mm forward, the weight of baggage we need to shift is:

$$\begin{aligned} \text{Weight shifted} &= \frac{1055 \times 20}{700} \\ &= 30.1 \text{ kg} \end{aligned}$$

Remember to re-work the calculation so that it accurately reflects your loading.



Remember to secure your load.

What Units?

Because many aircraft in New Zealand are built in the United States, weight and balance data is often in pounds and inches. As we are more familiar with kilograms in New Zealand one solution is to convert and annotate the arm figures with metres (or millimetres) in the Aircraft Flight Manual "Weight and Balance" section.

This is permissible because this section is not part of the approved Aircraft Flight Manual, but an even better solution would

be to produce a customised weight and balance form. Either way, the C of G limits can be copied from the “Limitations” section and similarly converted, and shown in metres.

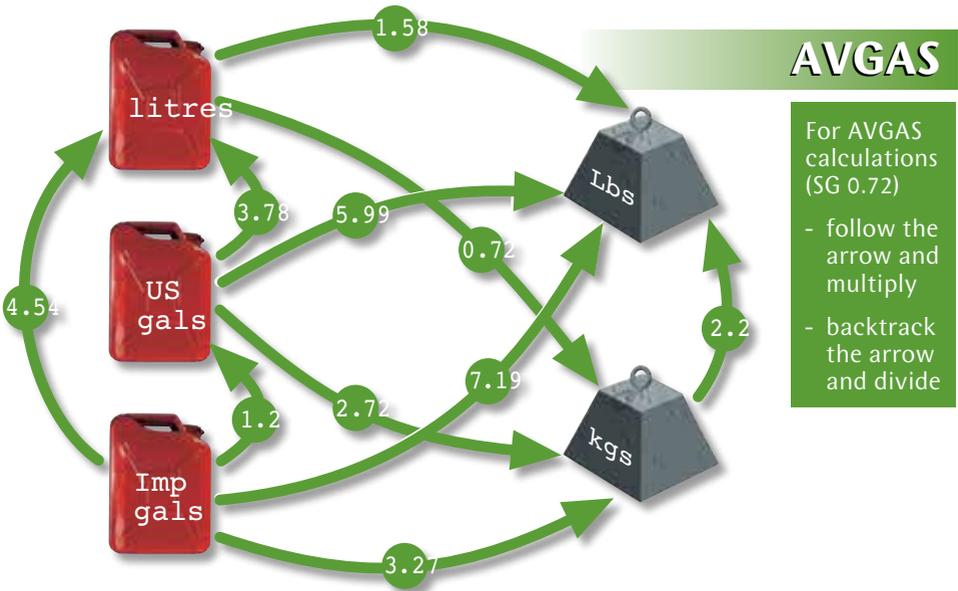
This one-off process is easier – and less prone to error – than having to continually convert passenger, baggage, and fuel weights to pounds.

An even simpler alternative is to use kilograms for weight but continue with inches for the arm. The resultant moment is thus in kilogram/inches. Although this is mixing units, it doesn’t matter because when the total is divided by the total weight, the resulting figure for the C of G is in inches, and this can readily be checked against the Aircraft Flight Manual “Limitations” figures.

Whichever method you use, make sure you know what units are being used, that they are the same units throughout, and that conversion factors are accurately calculated – have them double checked.

Conclusion

The average general aviation aircraft is not designed to be loaded with full fuel, max pax, and a baggage compartment crammed with suitcases, back-packs, golf clubs and camping gear, and still be expected to fly safely. Flying within the correct limits of weight and balance for the aircraft is vital for the safety of you and your passengers.





Sample Weight and Balance Form

Item	Weight	Arm	Moment
Units	()	x ()	= ()
Empty weight of aircraft			
Fuel			
Front seat occupants			
Rear seat occupants			
Baggage compartment			
Total weight and moment			
C of G position			
Limits	MAUW	C of G range	





PO Box 3555
Wellington 6140
Tel: +64 4 560 9400
Fax: +64 4 569 2024
Email: info@caa.govt.nz

Weight and Balance was reprinted in November 2014.
See our web site, www.caa.govt.nz, for details of more CAA safety publications.