



Understanding Weight & Balance

To “feel” the aircraft response through the flight controls as being “heavier or lighter” than anticipated at take-off can result from a weight & balance inaccuracy. In fact, when the CG is out of the operational limits, the safety consequences can be far more critical than just a strange feeling.

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What does actually lie behind the aircraft weight and the %RC or %MAC mentioned on the load and trim sheet? What do these limits account for? Beyond the compliance with regulatory requirements dimension, let's take a journey through the underlying physical phenomena at stake. But first let's take a look at what can happen when the loading and C of G is incorrect or becomes out of limits.

A VARIETY OF EVENTS, A COMMON ORIGIN

Images of airplanes sitting on their tail or experiencing a severe tail strike or even stalling right after take-off unfortunately do not all belong to the past. In recent years, commercial aviation has faced multiple accidents or serious incidents related to weight & balance issues.

Tail strike at take-off

While taking-off for the second leg of a flight, a single aisle aircraft experienced a tail strike. Despite significant damage, the aircraft was able to turn back and land at departure airport. The first leg had been uneventful. During the intermediate stop over, some of the passengers disembarked the aircraft and their luggage was offloaded. No new passengers boarded nor was any new cargo

loaded. The investigation revealed that the passengers proceeding to the second destination airport were all seated at the back of the cabin and their luggage was loaded in the aft cargo bay. No movement of passengers between legs took place. The load sheet had been prepared for the first leg only. The CG position for the second leg turned out to be outside of the safe envelope: it was too far aft.

Unexpected pitch-up during climb

The next story is based on a real event with a wide body cargo aircraft. The aircraft was carrying several similar heavy pieces of special cargo. During climb, the aircraft experienced an unexpected pitch-up when the

cargo detached and moved aft. The CG warning alert went off and the AP disconnected. The pilot successfully manually controlled the aircraft and eventually landed safely.

Tail tipping

While being unloaded, a wide body cargo aircraft tipped up on its tail. It turned out that a less than optimum shift handover had taken place, and

lack of training of the load master on the aircraft type contributed to the non-compliance with the correct unloading sequence.



DID YOU KNOW

Among the accidents related to a weight and balance issue*:

- 21% are due to overweight
- 35% are due to a CG which exceeds the certified limits

*National Aerospace Laboratory (NLR) study for the period 1997-2004

Tail strike and take-off after runway end

A long-range aircraft type failed to take-off within the runway length, and experienced a significant tail strike whilst ultimately managing to take-off way outside the runway limits. The aircraft was severely damaged but fortunately, was ultimately able to make a successful landing. The investigation revealed that the aircraft weight entered into the system to compute the take-off speed was incorrect. One digit was incorrectly entered. While the aircraft weight was 362 tons, the take-off performance data were calculated for a 262 tons aircraft, thus the expected performance was significantly over estimated. The real aircraft performance was much worse than that which had been calculated.

Stall and crash

Right after take-off, a long-range wide-body cargo aircraft experienced a violent pitch-up that couldn't be recovered by the crew. The rapid decrease in airspeed led to the aircraft stalling and crash. It turned out that the load had broken free and had shifted aft just after take-off.

Four recent events, one safety lesson: the impact of weight & balance issues on a flight can range from merely a "strange feeling" to a fatal accident. ■



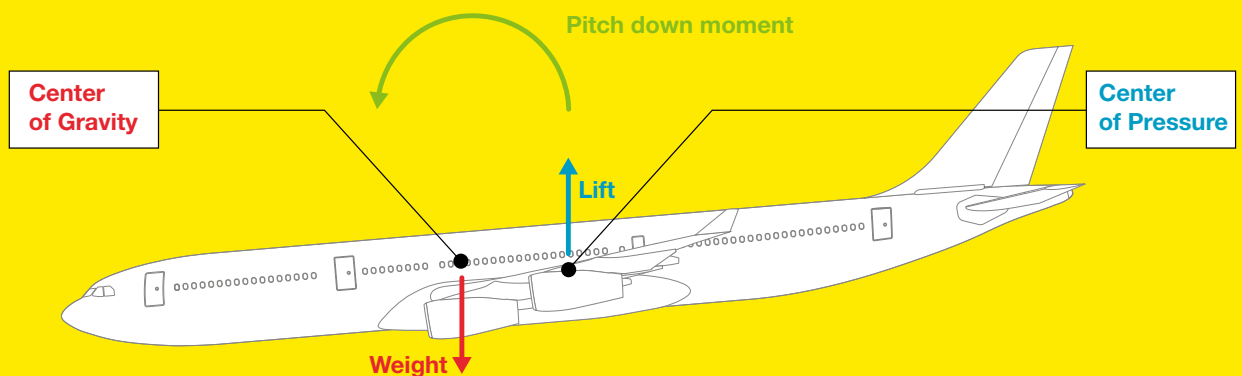
WEIGHT & BALANCE: WHAT IS IT ABOUT?

In order to well understand the impact of weight and balance on the stability and maneuverability of the aircraft, it is worth getting back to the forces that apply to the aircraft, and more specifically to focus on the vertical ones.

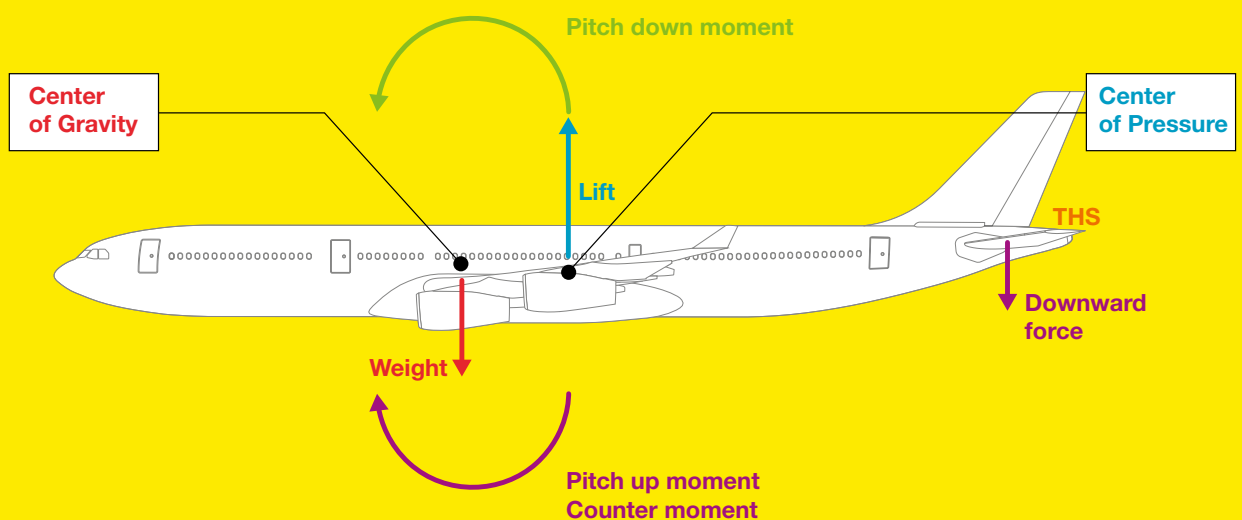
There are two of them, applying at distinct points along the aircraft longitudinal axis:

- The Weight of the aircraft, applied at the Center of Gravity (CG) of the aircraft;
- The Lift, applied at the Center of Pressure (CP).

The CG is further forward than the CP for aircraft stability reasons. Thus, the more distant the two points, the bigger the pitch-down moment.



The distance between the CG and the CP induces a pitch down moment that needs to be compensated for to keep the aircraft level. This is done through the Trimmable Horizontal Stabilizer (THS) that exerts a downward force. This force applies at the THS, thus far from the CG; therefore it creates a big pitch-up moment, but also increases the required overall lift to keep the aircraft level at the same time.



KEEPING THE CG WITHIN THE OPERATIONAL ENVELOPE: A MUST FOR A SAFE FLIGHT

The influence of the CG position on aircraft performance, stability and maneuverability varies along the flight, depending on the phase of flight. The main safety issues related to an inappropriate position of the CG depend on whether the CG is forward or aft as developed hereafter.

CG forward

As explained earlier, the more distant the CG and the CP, the bigger the pitch-down moment. Since for aircraft stability reasons the CP is always located behind the CG, a forward CG

increases the distance between the CP and the CG. A CG position further forward than the most forward position of the operational envelope can affect the safety of the flight in many ways.

» Impact on aircraft maneuverability at all phases of flight

A CG position that is too far forward induces such a big pitch-down moment that the aircraft maneuverability can no longer be guaranteed.

Indeed, the more forward the CG, the bigger the horizontal stabilizer and elevator deflections needed to give the aircraft a pitch-up attitude to compensate for the pitch-down moment. However, at some point of CG forward position, the horizontal stabilizer and elevator maximum deflections are reached, and the aircraft cannot

be maneuvered any more.

As an example for take-off, if the CG position is too far forward, the aircraft has such a “heavy nose” that the correct take-off rotation rate using the elevator becomes impossible to reach. The impact of an excessively forward CG position on aircraft maneuverability applies at all phases of flight. However, it is most noticeable at low speed due to the reduced effectiveness of the elevators.

“ A CG position that is too far forward induces such a big pitch-down moment that the aircraft maneuverability can no longer be guaranteed. ”



» Impact on aircraft performance at all phases of flight

A CG exceeding the most forward CG position of the envelope is also the most penalizing situation in terms of aircraft performance.

Indeed, the take-off and landing per-

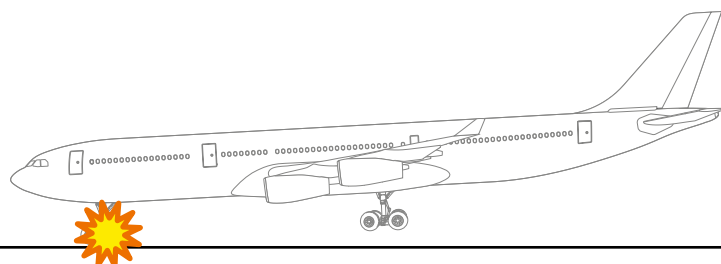
formance is calculated based on the most forward CG position within the envelope. Therefore, if the CG position is even more forward, the actual aircraft performance will be lower than the calculated one.

» Impact on aircraft structure at take-off

On the ground, the total weight of the aircraft is supported by both the nose and main gears, the further forward the CG, the bigger the proportion of total weight is carried by the nose landing gear. At high weights (TOW),

if the CG position exceeds the most forward CG position of the envelope, the aircraft structural limits of the nose landing gear can be reached with a consequent risk of damage.

“ A CG exceeding the most forward CG position of the envelope is also the most penalizing situation in terms of aircraft performance. ”



CG aft

A CG aft position brings the CG close to the CP. Yet, exceeding the CG most aft position of the envelope can lead to a variety of safety issues.



» Impact on aircraft controllability at ...

... Go-around

In case of go-around, setting TOGA power induces a significant pitch-up moment that needs to be compensated for. The more aft the CG, the bigger the pitch-up moment. If the CG is too far aft, and outside the envelope, the pitch-up moment induced by initiating the go-around may be too big to be compensated for.

At low speed, high angle of attack and TOGA power, the pitch-up moment increase due to having a CG position too far aft, may also trigger the alpha floor protection, thus prevent its sufficient compensation.

... Take-off

At lower take-off weight (for example for a positioning flight or short leg flight), a CG position too far aft impairs the nose wheel controllability during taxi and at the beginning of the take-off run. Indeed, the weight of the aircraft being mostly on the main gear, the adherence of the nose wheel to the ground is limited. This is especially true on wet or contaminated runway surfaces. Until the aircraft reaches a sufficient speed for the rudder to be effective, nose wheel steering is the only way to control the aircraft. The nose wheel adherence is even further reduced when full power is applied for take-off due the induced pitch-up moment.

This “very light nose” effect of too aft a CG position also makes the rotation so easy that it could as easily lead to a tail strike (**fig.1**). In some cases, the aircraft will “self rotate” without any action by the pilot.



(fig.1)

Tail strike at take off

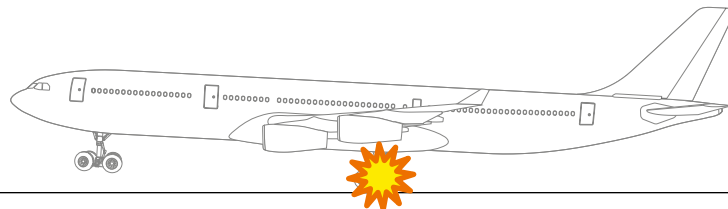


» Impact on aircraft structure at take-off

As mentioned earlier, on the ground, the total weight of the aircraft is supported by both the nose and main gears. Therefore, the further aft the CG, the bigger the weight on the main landing gears. At high weights (TOW), if the CG position exceeds the most aft CG position of the envelope, the aircraft structural limits of the main

landing gear can be reached with a consequent risk of damage.

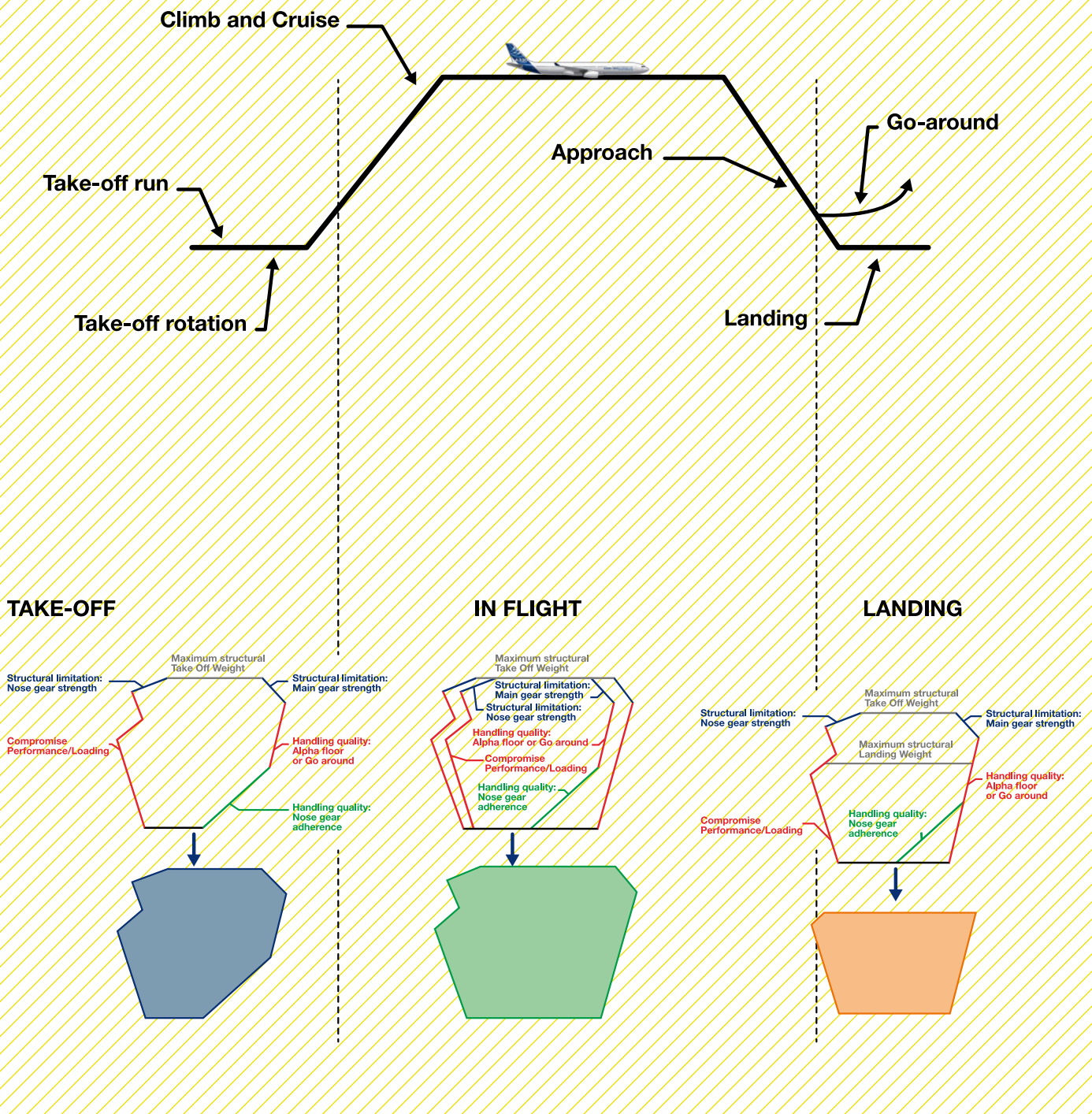
Likewise, in such high TOW conditions, the load on the wings may exceed their structural limit. This is the reason why the speed is limited during taxi for turns.



Eventually, a CG outside the operational envelope may significantly impair the aircraft capabilities, and thus ultimately jeopardize the safety of the flight. ■

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Summary along the flight path of the main safety impacts of an ill-located CG



HOW TO MAKE SURE THE CG IS AND REMAINS WITHIN A SAFE ENVELOPE THROUGHOUT THE FLIGHT?

Both the CG position and the safe envelope evolve throughout the flight. Indeed, the weight of the aircraft evolves mainly as fuel is burned. As for the CG, its position is sensitive to various phenomena ranging from landing gear, flaps and slats position to passengers or cabin crew movements from one end of the cabin to the other.

Although there were attempts at developing systems to measure the aircraft weight and CG position, no robust solution has yet been found. The best way to make sure the CG remains within a safe envelope throughout the flight is to both define

an operational envelope that includes safety margins and to perform a correct CG calculation. Indeed, as explained in the previous section, an excursion of the CG outside of its operational envelope could lead to dramatic consequences.

Understanding the safety margins

Determining the CG safe envelope results from calculations based on a number of assumptions. These assumptions are simplifications of the actual but evolving aircraft situation. They include inaccuracies and uncertainties that need to be compensated for. This is the purpose of the safety margins taken to define the operational envelope. Among the sources of inaccuracies and uncertainties are:

- **The determination of the dry operating weight of the aircraft:**

This weight is based on the aircraft weighing results and on assumptions on the weight of items on board such as catering or crew. From one weighing to another the aircraft weight may evolve;

- **Weight of passengers and their hand luggage:** In the CG determination a single average passenger weight is taken into account to reflect as much as possible the reality.

- **Passengers embarkation:** Some changes in passengers seating may occur either before or during the flight. Their impact on the aircraft

actual CG position is usually limited. In case of free seating though, some significant difference may exist between the actual and the calculated CG positions with potential impact on safety (see insert *Free seating section*);

- **Moving parts of the aircraft:** The CG position is calculated based on a given aircraft configuration. Yet, in the course of the flight, the aircraft configuration evolves: flaps and slats are retracted, landing gear moves up...;

- **In-flight cabin movements:** A single passenger moving from one end of an aircraft to the other is sufficient to affect the CG position.



DID YOU KNOW

On an A320 37,57m long, the maximum distance along which the CG position may move is 1.34m i.e 4%.

On an A380 72.57m long, it is 1.97m i.e 3%.



DID YOU KNOW

On an A320, a duty free trolley of 150kg rolling from the back end to the front of the aircraft moves the CG by more than 5cm out of a 1.34m leeway.

- **Cargo loading:** Although there are relatively few errors on the cargo weight there may be some in the distribution of containers;
- **Fuel weight and distribution:** The fuel density used to perform the calculation is not always the actual density. It is indeed quite sensitive to temperature. A tank full in volume doesn't always correspond to the same weight. In some cases,

the difference may require to fill in the trim tank with a significant impact on the CG. The fuel logic of the A340-500/600, A380, 350 is based on weight rather than volume. Therefore these aircraft types are less sensitive to this aspect;

- **Calculation method:** The figures used to calculate the CG position are rounded off.

FREE SEATING: FREEDOM UNDER CLOSE SCRUTINY

As a passenger, choosing your seat at the very last minute, when entering an aircraft relatively empty may be exciting. From a weight and balance viewpoint, it is another story. Free seating means uncertainty in terms of CG position, thus special caution to make sure the CG is within operational limits. Indeed, if free seating doesn't affect the total weight of the aircraft, it affects weight distribution, even more so if the cabin is not fully occupied.

In order to determine the aircraft CG position, the aircraft cabin is divided and modeled in several sections, usually 2 to 4. The aircraft CG position is calculated based on each section's weight and relative CG position. The assumption is that passengers are at the barycenter of the section.

When less than 80% of the seats are occupied in the cabin, not knowing where the passengers are seated may lead to a difference between the actual CG and the calculated one that can reach 2 to 3%. This translates into a significant difference between the actual and expected aircraft behavior.

The pilot will trim the aircraft for take-off using the calculated CG. If at take-off, the actual aircraft behavior is different from the expected one, the risk is that the pilot overreacts to this discrepancy. The type of reaction will depend whether he/she feels the aircraft nose too heavy or too light.

In order to prevent this, except for A318/319 where the cabin is small enough, it is needed to split the cabin into at least 3 sections to have sufficient precision.

Ensuring consistency between actual operations and load and trim sheet calculations

For each flight, a load and trim sheet is to be developed to ensure the CG will remain within the operational envelope. A number of assumptions are made when doing so. Ensuring that the calculated CG corresponds to the actual aircraft CG requires consistency between these assumptions and the actual operational framework and practices. Among the aspects that can challenge this consistency are:

- **Assumptions on the weight of passengers and their hand luggage:** The average weight to be considered for a passenger and his/her carry-on luggage is mentioned in regional regulations. Yet, in some regions, the assumptions date back from quite a long time whereas a variety of sociological evolutions have taken place. The average weight of passengers tends to increase. So does the weight of car-

ry-on luggage with new items commonly taken onboard such as computers, cameras, cell phones...;

- **Last minute changes:** To load a container at the last minute is an operational practice that may significantly impact the aircraft weight and balance. If not updated accordingly, both the weight of the aircraft and the CG position calculated are incorrect (see insert *Last minute changes*);

- **Fuel burned during taxi:** In reality, the impact of the fuel burned for taxiing on the CG position is very limited. The fuel mainly comes from the inner tanks. For a while, some people in the industry held a serious mis-conception as they believed that the fuel burned first was that of the tank filled last, namely the trim tank (for aircraft equipped), which is not the case in reality.

Eventually, if the calculation underlying assumptions are realistic, the calculated CG position is as good an estimate as possible. Still, in order to compensate for a number of inaccuracies, safety margins are required to make sure that the CG will remain within a safe envelope throughout the flight. These margins are the ones that allow for defining the operational envelope.

LAST MINUTE CHANGES

To load a container at the last minute, because “there is room for it” is tempting for an airline. Recalculating the weight and CG position “at the last minute” is no option from an operations viewpoint for the delay it would induce. Yet, from a safety standpoint, a last minute change involves not only an increase in weight but also a change in the CG position that need to be considered carefully to avoid an excursion of the CG outside the safe envelope in the course of the flight. A good compromise that allows for reconciling the two perspectives is to calculate the maximum impact of LMCs and integrate it into the safety margins calculation.

Keeping the CG within a safe envelope throughout the flight: a collective effort

As mentioned earlier, the CG safe envelope depends on the aircraft weight. As for the CG position, it depends on the weight distribution along the aircraft. In practice, making sure the CG remains within the operational limits relies on a wide range of actors and actions that can be summarized as follows:

Actor	Actions
Airbus	Provide the aircraft weight at delivery, and raw data on positions and maximum weight of elements that can be loaded. Provide also the CG and Weight limits applicable to the aircraft
Airline ops	Determine the operational limits (one for Take-off and another one for Zero Fuel).
Load planner	Prepare a load sheet ensuring the CG remains within the operational limits: one per segment/flight.
Load master	Load and secure the cargo at the anticipated places. Load and unload according to the predefined sequence.
Pilots	During the walk around, visually “notice” the contraction/extension of the landing gear oleos and also the angle of any nose wheel steering link to carry out a gross error check for loading normally. Type in the correct values into the aircraft systems to compute aircraft performance. Cross-check aircraft performance with the other pilot. Check the CG is within the operational limits.

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